MORPHOLOGY OF THE LOWER MISSOURI RIVER: THE PROCESSES INVOLVING DEVELOPMENT OF HIGHLY SINUOUS GOOSENECK LOOP CUTOFFS EXPOSED IN THE SURFICIAL DEPOSITS OF THE RIVER FLOODPLAIN

by

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Dejuan Jackson and especially Dr. Andrew Hardin. Just by being who they are, they inspired me to be a smarter and better person even inspiring me to return to college. Thanks guys.

November 23, 2011

ABSTRACT

MORPHOLOGY OF THE LOWER MISSOURI RIVER: THE PROCESSES INVOLVING DEVELOPMENT OF HIGHLY SINUOUS GOOSENECK LOOP CUTOFFS EXPOSED IN THE SURFICIAL DEPOSITS OF THE RIVER FLOODPLAIN

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Mapping the surficial deposits of the Missouri River from Sioux City, Iowa to Mondamin, Iowa brought to light a prominent set of landforms exposed in the floodplain and which are also easily visible via aerial photography. The landforms are segments of highly sinuous channel fills that exhibit the characteristic of turning up-dip against the natural southern gradient of the river valley. These prominent channel scars, of which there are only five exposed in the study area, take on a recognizable “gooseneck” shape. The allostratigraphy for the reach of the Missouri River floodplain from Sioux City to Mondamin was mapped during the summers of 2009 and 2010. Soil samples were collected in the loops for OSL dating to determine the ages of these loops and determine any time relationship between them. The purpose of this study is to assess how they initiated, developed and evolved. The gooseneck meanders in this study developed via a combination of westward river migration owing to later valley tilt by tectonic

uplift and river mechanics on the margins of braided and meandering conditions that temporarily and randomly force the Missouri River into a runaway meander pattern when meandering is locally achieved. They loops eventually succumb to neck cutoff.

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CHAPTER 1

INTRODUCTION

The Missouri River is considered a major river in the contiguous United States, as well as a major tributary of the Mississippi River system, but from a geological standpoint very little is known about this river. The Missouri River valley formed in the Pleistocene as a result of glacial ice disruption (Fenneman, 1938; Warren, 1962), and it has undergone extensive changes in its short life. Some of this history is still preserved in the alluvial floor of the Missouri River valley, especially in what is referred to as the Lower Missouri River valley from Sioux City, Iowa to its confluence with the Mississippi River near St. Louis, Missouri. This reach of the Missouri River was straightened and channelized by the U.S. Army Corps of Engineers in the mid 1900s. This channelization prevents the Missouri River from undergoing its normal side to side migration patterns and thus allows us a glimpse of some of this preserved history in the floodplain covering the valley floor, which otherwise might be removed by recent meandering. The valley alluvium exhibits a number of highly sinuous meander channels left behind by past river migrations (Figure 1.1). Most of these channel loops have wide open arcs, but some form the recognizable shape of a goose head or "gooseneck" (c.f., Carson and Lapointe, 1983).

The purpose of this Master's Thesis is to determine the fluvial processes that resulted in the formation of these "gooseneck" meanders. The allostratigraphy of various stretches of the Missouri River floodplain have been mapped from South Dakota to Iowa, Nebraska and Missouri over the last 10 years under the supervision of Dr. Holbrook and others, yet these highly sinuous "gooseneck" loops have only been identified in the 2009 and 2010 project areas thus far. My study was based on the hypothesis that the loop formations were attributed to a large change in sediment supply and discharge as opposed to tectonic or bedrock controls. Data collected during this study in combinations with the current database of maps, soil data and chronological dating of Optical Stimulated Luminescence (OSL) samples provide the data base to test this hypothesis.

1.1 Study Area

The geological focus of this research is along a segment of the Missouri River Valley starting at the north end from Sioux City, Iowa ending at Mondamin, Iowa to the south (Figure 2.1). Sioux City, Iowa is the area where the Missouri is converted from its braided state to its forced channelized form all the way to its confluence with the Mississippi River near St. Louis. Further north of Sioux City, the Missouri River flows through a narrow valley cut towards the east in Cretaceous rocks consisting of interbedded shale, sandstone and limestone (Nebraska Conservation and Survey Division, 1996; Martin et al, 2004; Johnson and McCormick, 2005; Elliot and Jacobson, 2006) until it reaches Yankton, South Dakota where the river valley widens considerably and bends more towards the south. Between Yankton, SD and Sioux City, IA, the Missouri River hugs the southwest valley wall. At Sioux City, the valley narrows down to 6.4 – 7.2 kilometers before bending further south and becoming wider. The approximately 6.4 km gap at Sioux City acts as a "bottleneck" where the Missouri River stops hugging the southwest valley wall, crosses the valley, hitting the Northeast wall, where it is redirected further to the south by the opposite bedrock wall. After the redirection by the East valley wall at Sioux City, the river crosses the valley again and continues hugging the west valley wall (Figure 1.2).

The Missouri River Valley reaches widths of up to 32 kilometers wide, but not dropping below 16 km in width until it narrows again 15.6 km north of Omaha, NE. The stretch of valley from Sioux City, IA to its narrowing north of Omaha is 121 to 128 kilometers long. The focus of this research is along the northern 98 km of the Missouri River Valley, from Sioux City, IA to Mondamin, IA. The channel belt of the Modern Missouri River spreads across the valley floor reaching widths of 11.3 to 16 km wide, but it never intercepts both sides of the valley except at the bottleneck locations at Sioux City, IA and Omaha, NE.

During the summers of 2009 and 2010 graduate and undergraduate students, mapped the surficial deposits of the Mississippi flood plain of which these aforementioned “gooseneck” loops stood out prominently amongst the confusing multitudes of morphological changes.

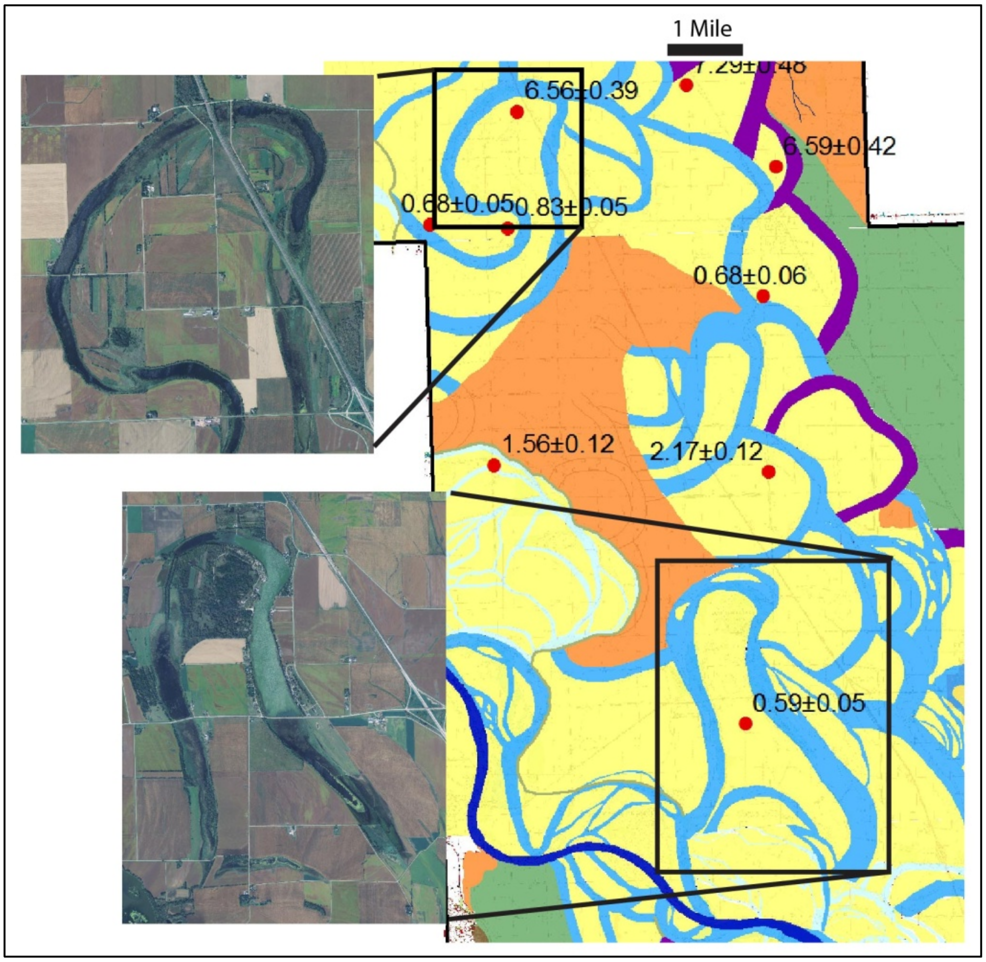


Figure 1.1: Two Gooseneck meander loops exposed in the Missouri River floodplain.

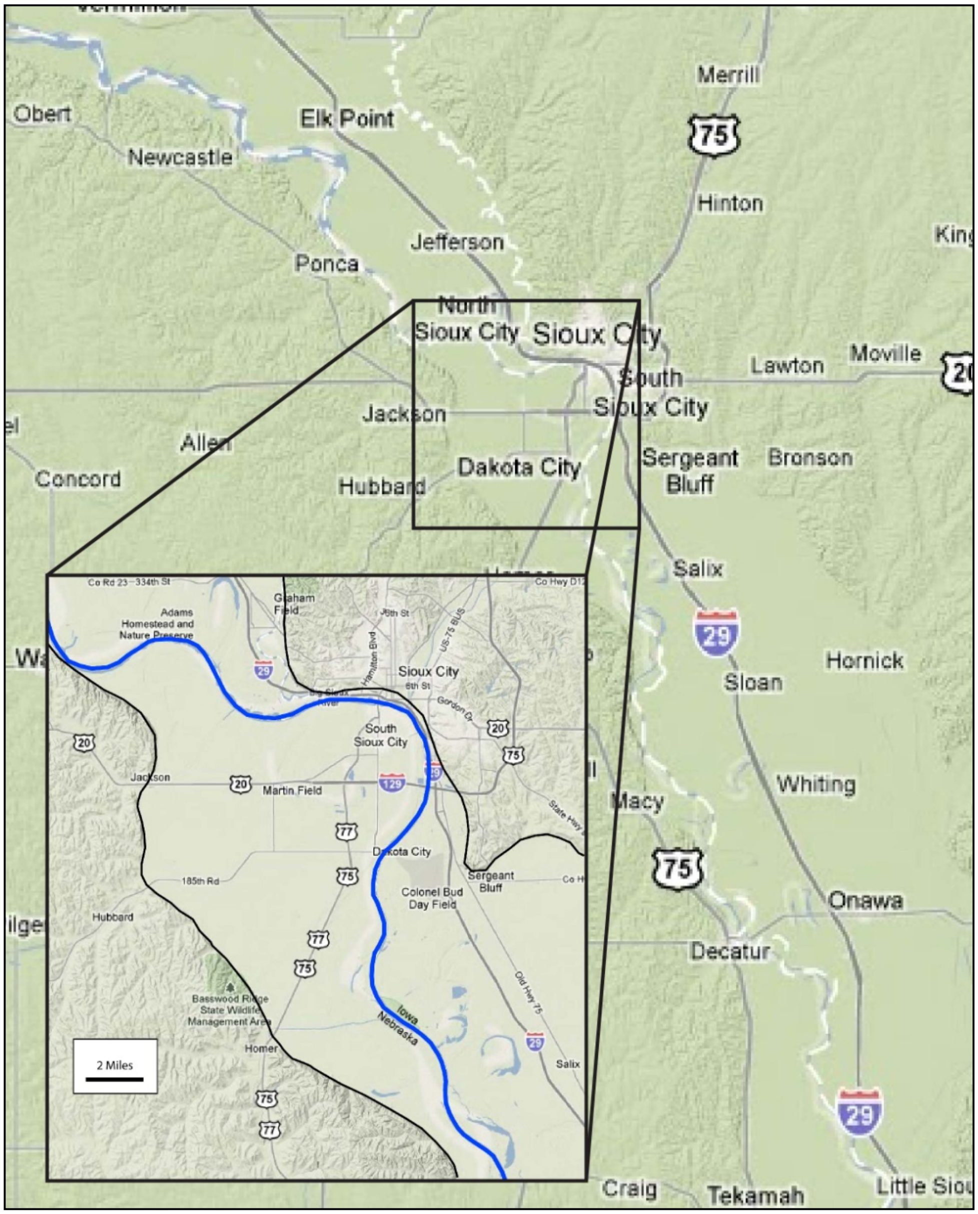


Figure 1.2: The Missouri River crosses its valley at Sioux City, IA. (Inset) Black lines represent bedrock valley walls of the Missouri River Valley. The blue line is the Missouri River crossing the valley and redirected back towards the west valley wall.

CHAPTER 2

BACKGROUND

2.1 The Missouri River

The Missouri River drainage basin has the largest drainage area of the Mississippi basin, draining about one-sixth of the United States. Before the damning of the river at six locations along its length, the furthest south is at Sioux City, IA; the river and its tributaries provided 70% of the Mississippi's sediment load (Moody et al, 2003) (Figure 2.1). The Missouri River basin covers 10 states and extends partially into Canada (Figure 2.2) and is divided into an upper and lower valley. The upper river valley has six power/flood-control/recreational dams with a water area of over 1 million acres which feeds into the lower river valley. The lower river valley has been straightened into a navigable channel by the U.S. Army Corp of Engineers. Organizations such as the Army Corps of Engineers and the Fish and Wildlife Service as well as private institutions are involved in constant debates over competing issues of channel navigation, habitat availability, river restorations and floodplain development of the Lower Missouri River and how best to balance commercial, ecological, and recreational needs.

Most recent studies on the Missouri River are largely dedicated to non-geology fields such as archaeology and ecology, while studies on the geology of the Missouri River are, unfortunately, more limited. The Missouri has not undergone the level of geologic study of the confluent Mississippi River Valley (e.g. Saucier, 1994; Blum, 2000; Knox, 2003; Rittenour, 2007; Guccione,M., 2008). Guccione's (2008) work on the Missouri River near the Mississippi confluence is mostly archaeological in nature though some geology is utilized in her research of ancient population sites on the river. There are ecological studies dealing largely with wetlands preservation, and multiple studies concerning fish population and development. For instance, Braaten's (2010) work involved the spatial distribution of Pallid Sturgeon young released and then sampled further down river to determine movement patterns. Steffensen (2010) released a study the survival rate of stock raised Pallid Sturgeon, which are later released into the Lower Missouri River to try and determine methods of maintaining their population in the river. There are also technical reports released by the Army Corps of Engineers (Branyan, 1974) regarding the engineering and channelization of the Missouri River.

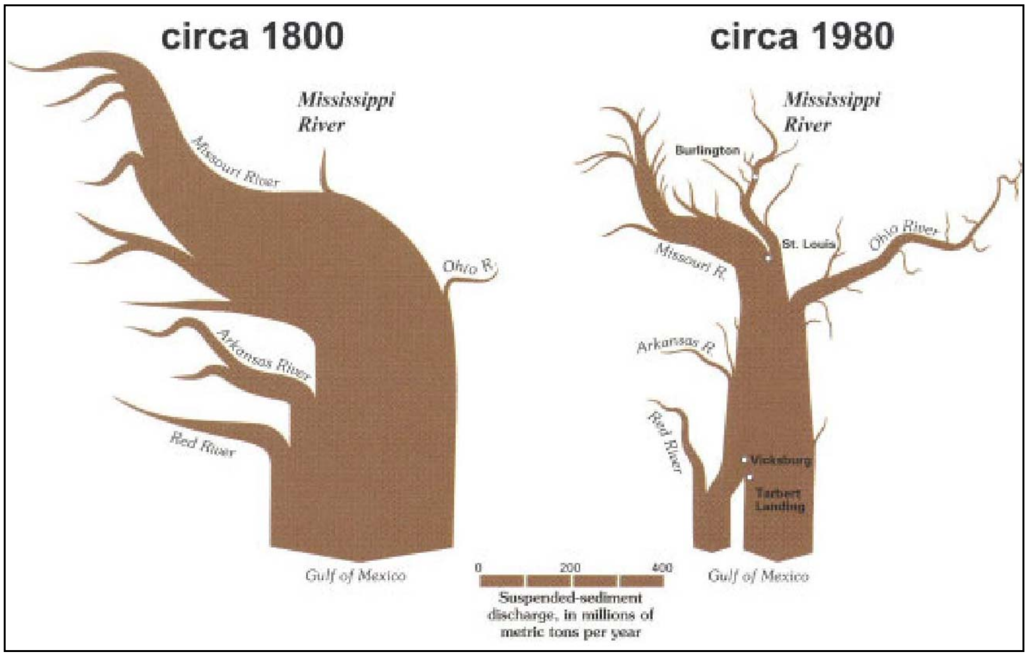


Figure 2.1: The sediment load of the Missouri River prior to (circa 1890) and post (circa 1980) human development. (Meade & Moody, 2009)

While previous geologic work on the Missouri River is limited, it still exists. Halberg et al (1979) released a study via the Iowa Geological Survey discussing the changes the Missouri River has experienced from 1876 to 1976. Heine and Lant (2009) have looked into the temporal patterns of stream channel incision of the Missouri River as it is trying to reach dynamic equilibrium. Meade and Mood (Moody et al, 2003; Meade & Moody, 2009) also have conducted studies on the Modern Missouri involving river discharge and sediment capacity. Meade and Moody (2009) state that the construction of a number of dams along the Upper Missouri river caused a decrease in the amount of sediment load in the Missouri River. The decrease in sediment load has resulted in increased incision downstream of the damn locations as the river tries to bring itself back to sediment capacity. The Missouri River is still the main contributor of sediment to the Mississippi River, but has decreased input by over half (Figure 2.1).

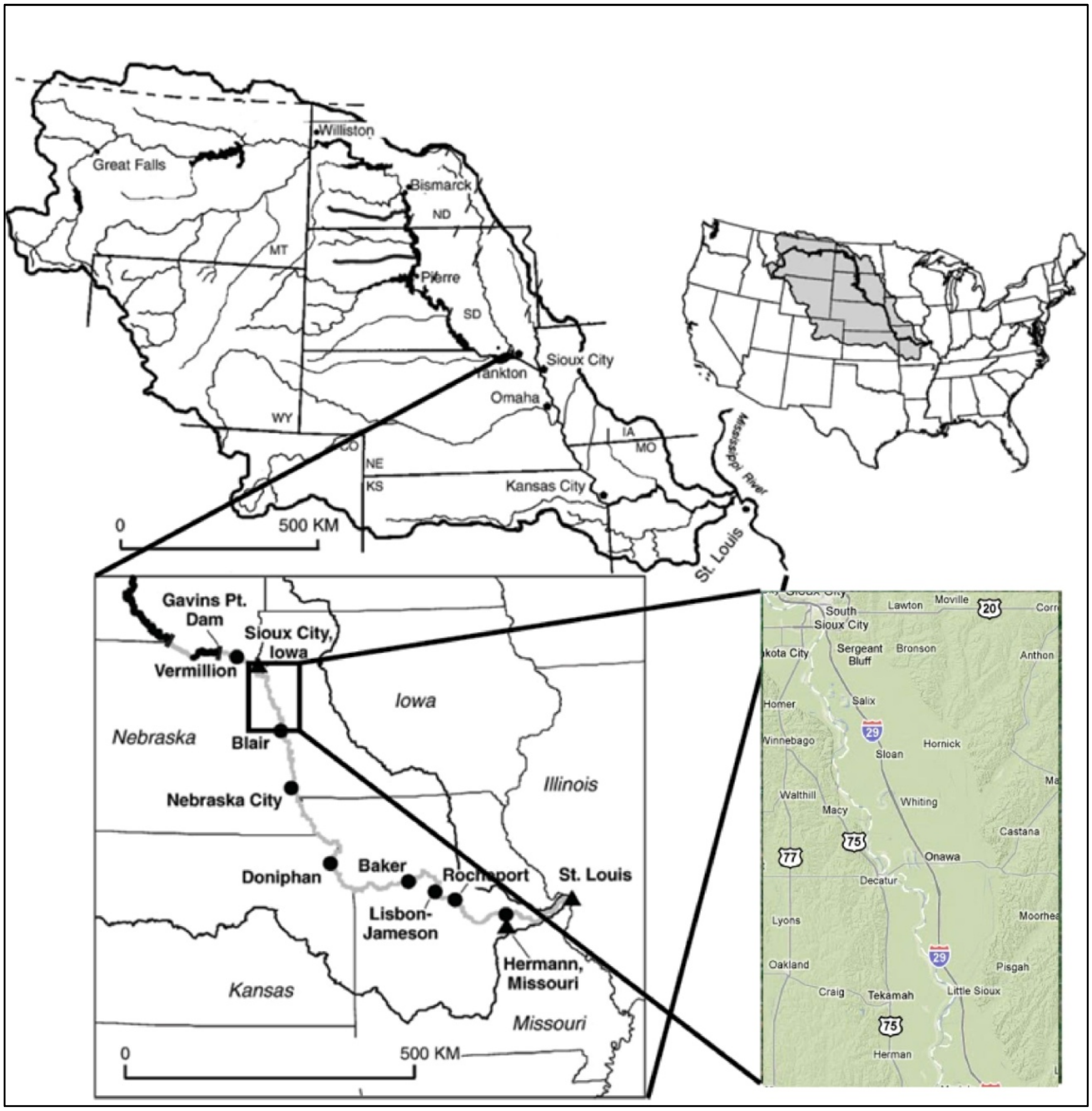


Figure 2.2: The Missouri River Basin. The inset at the bottom right is the research location.

Peggy Guccione and EDMAP students mapped the area of confluence of the Missouri and Mississippi rivers at St. Louis in 2005. Joe Mason mapped a small part of the floodplain near Omaha, NE in the Fort Calhoun Quandrangle in 2001. Works by Jacobson (2006) and Kelly (1996) involve extraction and protection of future water supplies concerning quantity and quality of public water supply, rates of contaminant migration and connections between surface and groundwater flow. Scott Lundstrom with the USGS Denver office has worked with John Holbrook in creating surficial maps of the Missouri River valley from Yankton, South Dakota to Sioux City, Iowa.

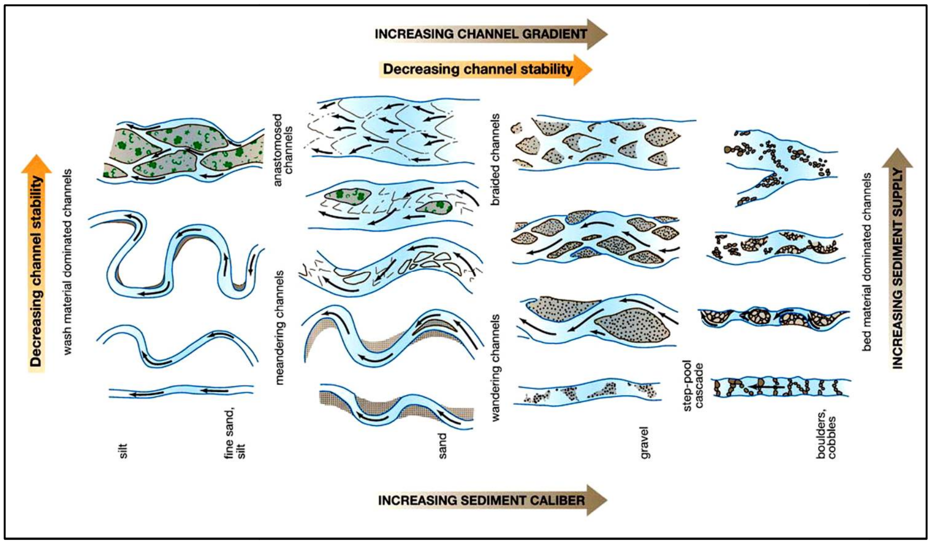
Elliot and Jacobson (2006) released an extensive report on the geomorphic classification and assessment of channel dynamics relating to the segments of the Missouri River. The focus of the paper was along segments of the upper Missouri River where it is allowed to stay in its natural braided state. Though bank stabilization, damming and other channel management reduces the Upper Missouri's capacity to migrate as freely as it once did, this northern length of the Missouri still provides a decent representation of a pre-human Missouri River braided system.

Other current work on the Missouri Floodplain involves John Holbrook's mapping of the surficial alluvium of the valley floor. His efforts along with students funded by NSF-REU and EDMAP have published the first 35 detailed 1:24,000 geologic quadrangle maps of the valley floor alluvium along the Missouri River valley. Ten of these maps are of a contiguous 53 kilometer alluvial reach of the main Missouri trunk system in Overton Bottoms North Unit of in the Big Muddy National Fish and Wildlife Refuge near Columbia, Missouri to the Missouri City area just east of Kansas City, Missouri. This series of maps has already revealed insights into the river processes and drainage-basin dynamics which generated the current river and valley system. Mapping also included stretches of the Missouri River valley from the Dakotas down into Nebraska and Iowa. An additional 10 maps from 2009 are expected to be released soon. In the summer of 2010, Holbrook and his students began work on an additional 6 quadrangle maps spanning from the Tekamah NW Quadrangle in Nebraska to the Mondamin Quadrangle in Iowa.

2.2. Fluvial Systems

There are large numbers of studies on specific braided and meandering rivers of which there are too many to mention in this work; however, there are many key studies which focus more specifically on formation, changes and controls on river systems that are directly applicable to this study. First, the geometry (as well as water flow, sediment transport, erosion and deposition) of river channels and floodplains are controlled in part by water supply and available sediment, which are controlled by the nature of the drainage system, regional climate, and tectonics. Changes in topography and accommodation space associated with tectonics and base-level changes are also controls on geometry, flow and sedimentary processes in alluvial systems (Leopold and Wolman, 1957; Schumm, 1985; Bridge 2003, for review). River channels vary in shape from straight to highly sinuous to braided although straight channels are merely channels with sinuosity so low they are generally referred to as straight (Figure 2.3).

To determine how these gooseneck meander loops formed, a good knowledge of river systems is required. We don't have specific data on flow velocity, river capacity and discharge rates of the Missouri River during the time these meander bends formed, we only have the preserved remnants in the valley alluvium and the surrounding geology to piece together the puzzle of their development.



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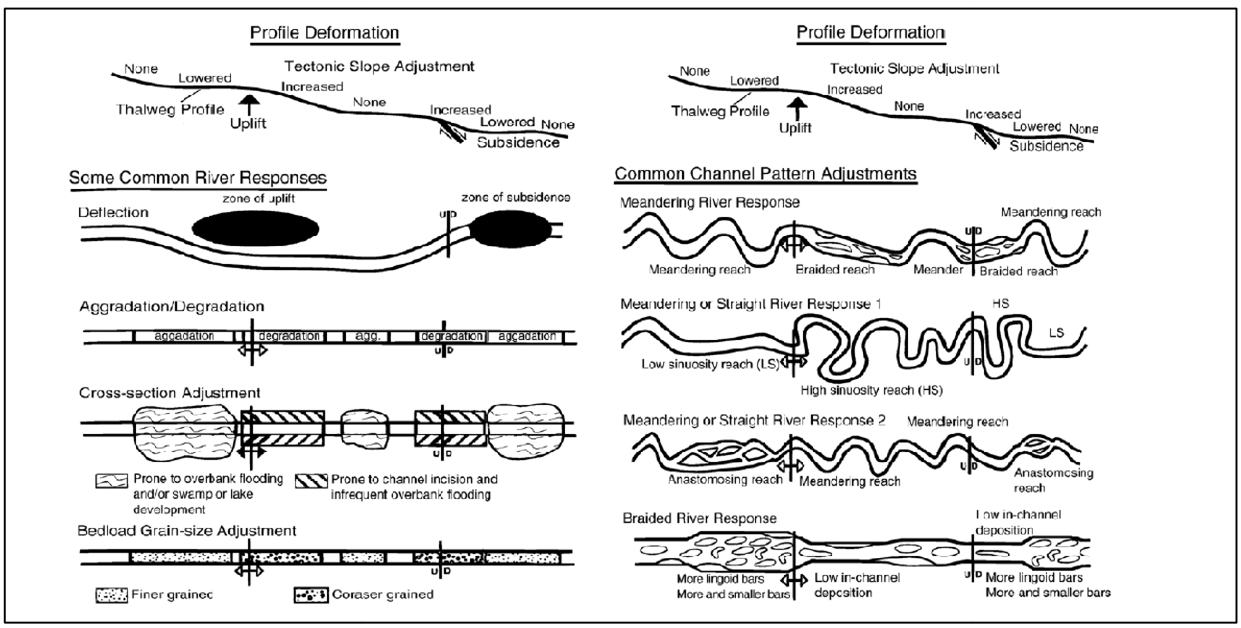


(b)

Figure 2.3: Concepts of influences on channel pattern (a) the effects of slope, water discharge and sediment load, (b) the effects of tectonics on pattern downstream. (a: Church, 2006), (b: Holbrook and Schumm, 1999).

2.2.1 Channel Pattern

Leopold and Wolman (1957) provide an in-depth look at river channel patterns. Much of their research involved testing fluvial systems through laboratory flume experiments and comparing their results to natural rivers. Braided river patterns were susceptible to changes in bank stability and slope due to their usually high sediment load and a lack of concentrated stream power owing to high width/depth ratio and turbulent water flow. If a braided river with high sediment load encountered an inclined or resistant surface, the river would divert around it toward an easier gradient. Leopold et al. (1960) also include that the addition of vegetation can increase bank stability under certain circumstances. Jackson's (1975) study of channel patterns along a reach of the lower Wabash River of Illinois and Indiana showed how one particular meander bend butted up against the bedrock valley wall. The meander loop, unable to migrate laterally, migrated up-dip against the valley gradient where the valley material was more easily eroded (Figure 2.4).

Brice (1974) studies the evolution of meander loops. His studies show how meanders start as relatively flat, simple symmetric or asymmetric shapes with a large radius of curvature and, over time, can develop into compound symmetrical and asymmetrical loops. Simple asymmetric meander loops have a tendency to rotate up or down valley dip. Simple loops, symmetrical or asymmetrical, can become compound loops when a second arc along its perimeter develops into another loop on the same side of the river (Figure 2.5).

Schumm (1981; 1985) builds on Leopold and Wolman (1957) and Brice (1974) by developing a river classification. He recognizes a set of 5 pattern types of fluvial channel via pattern variability such as stability and thresholds, metamorphosis and controls that determine their patterns. Schumm (1977; 1979; 1985; see also Holbrook and Schumm, 1999) also recognizes that the patterns of alluvial rivers are maintained by geomorphic thresholds that influence whether a channel will be straight, meandering or braided (Figure 2.3b). Water discharge, slope, bed material size and sediment supply impacts river sinuosity and whether it will meander or transition to a braided system. A change in one or more of these can result in a shift between patterns (Figure 2.6).

Hooke (2007b) talks about the behavior of meandering rivers and describes that meanders are always changing, but how fast or how slow depends on factors such as slope, water supply, bed material, discharge and bank stability. Meanders can become highly sinuous, but as Stolum mentions and Hook agrees with they can reach a criticality in sinuosity where they will eventually result in cutoffs; however, maximum flow capacity or flooding is required to trigger such cutoffs (Stolum, 1996; Hooke, 2007b). Mechanisms such as incision, bedrock and vegetation can hinder cutoffs. The most active meanders seem to be in the most erodible material and can exhibit sudden growth.

Duan and Julien (2010) developed a numerical model to simulate the evolution of meandering channels. The model incorporates the complex interactions between downstream and secondary flows, bed load and suspended load sediment transport and bank erosion. The model was able to simulate the evolution of straight channels into high sinuosity channels including, 1) downstream and upstream migrations, 2) lateral extensions and 3) rotation of meander bends. Duan and Julien's research also agreed with observations by Larsen (1995) whose own research was focused on the Mississippi River.

Larsen observed that while 40% of the Mississippi's old loops exposed in the valley floor turned downstream, 60% of the meander loops were turned upstream. Duan and Julien's simulations showed similar ratios of loops rotating up and downstream. Their simulations did also produce some gooseneck loops. Duan and Julien indicate that the direction the head of the loop turned was dependant on the flow momentum transition zones; at what point does the water flow transition from the convex outer bend of one bank across the channel to the opposite, outer bank of the next loop. If the momentum transition zone was at the apex then the meander migrated laterally. If the momentum transition zone was immediate upstream of the bend apex then the loop migrated upstream with the possibility of developing a gooseneck loop; otherwise the loop rotated and migrated downstream.

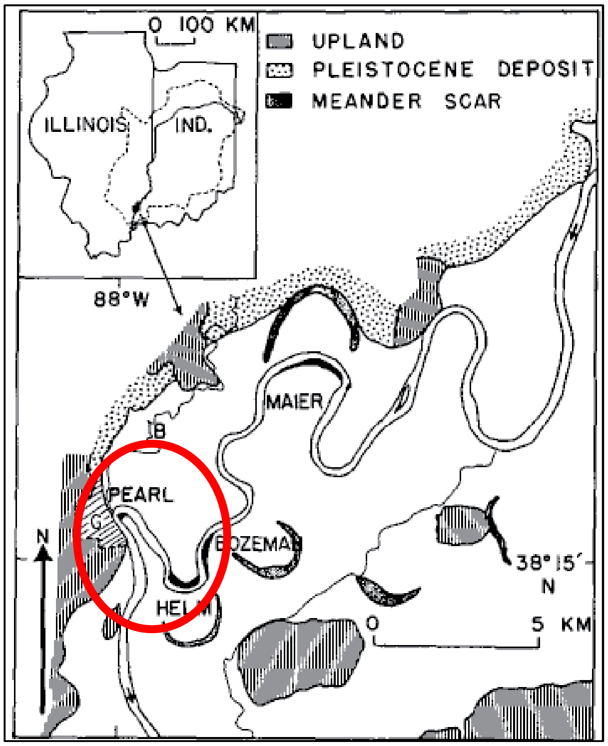


Figure 2.4: Pearl bend on the Wabash River in Illinois-Indiana migrating up-dip. The channel is pushing against the bedrock and migrating up-dip against the valley slope. (Jackson, 1975)

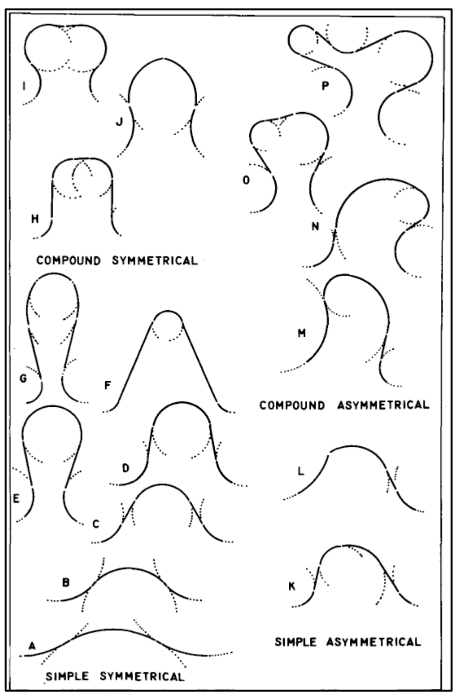
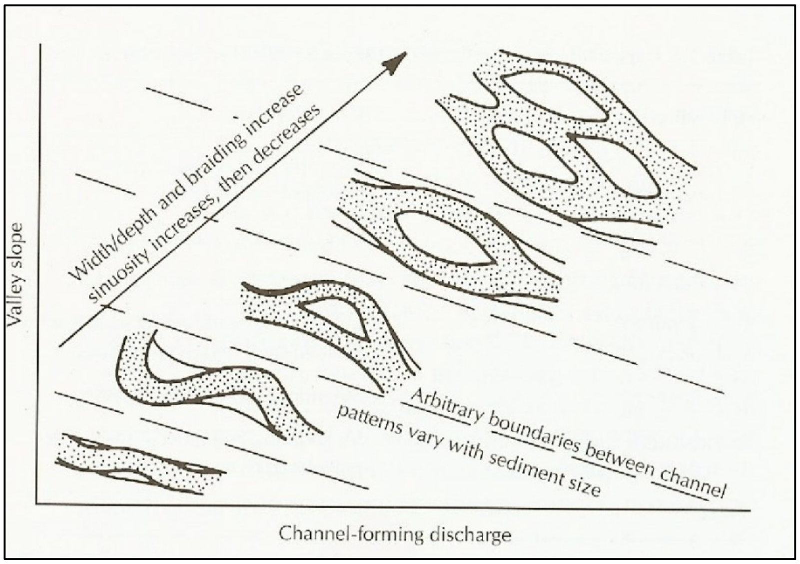


Figure 2.5: Meander Loop development. Starting out simple (bottom shapes) and evolving into more complex forms (top shapes). (Brice 1974)

Earlier work by Carson and Lapoint (1983), similar to Duan and Julien (2010) and Larsen (1995), studied the natural asymmetry of reaches of rivers that had exhibited highly sinuous planforms. They observed that some rivers in confined valleys tended to turn upstream when working through the alluvium of unconsolidated Quaternary sand resulting in predominantly convex down valley facing loops due to their inability to migrate laterally. They also state this is also possible for rivers in unconfined valleys that have the freedom to migrate freely about the floodplain. Carson and Lapointe (1983) provide examples of river stretches that show an inherent tendency to turn upstream and sometimes develop into “goosenecks.” Depending on what point in the meander loop the strongest part of the river current traverses across the river to the next bend can determine the shape of the channel. If it crosses early enough it can cause erosion earlier in the loop forcing the head of the meander bend to turn upstream instead of migrating laterally or rotating downstream. The process over meander bends rotating up or downstream can propagate up and down stream.

Bridge (2003, for review) summarizes many studies of single curved river (Brice, 1974; Hooke, 1977) and braided river channel-migration patterns (Leopold et al, 1964; Bridge et al, 1986; Thorne et al, 1993). Flow patterns in curved channels can vary depending on flow stage and plan geometry. At high flow stage, the increased water velocity will act on the outer bank of a meander bend downstream of the bend apex. At low flow stage, the peak water velocity will exert shear stress on the outer bend of a meander upstream of the bend. If bank erosion can occur at relatively low flow in cohesion-less sand then banks upstream of the bend apex can be eroded. However, if bank erosion is limited to flood stages then erosion will occur downstream of the bend apex of a meander.



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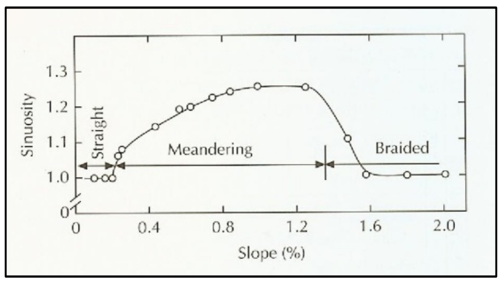


(b)

Figure 2.6: Channel pattern change: straight, meandering of increasing sinuosity eventually shifting to a braided system (a) the effects of slope, sediment load and size, (b) Similar to (a) but graphed via increasing sinuosity (a: Bridge, 2003), (b: Schumm & Khan, 1972; Bridge (2003).

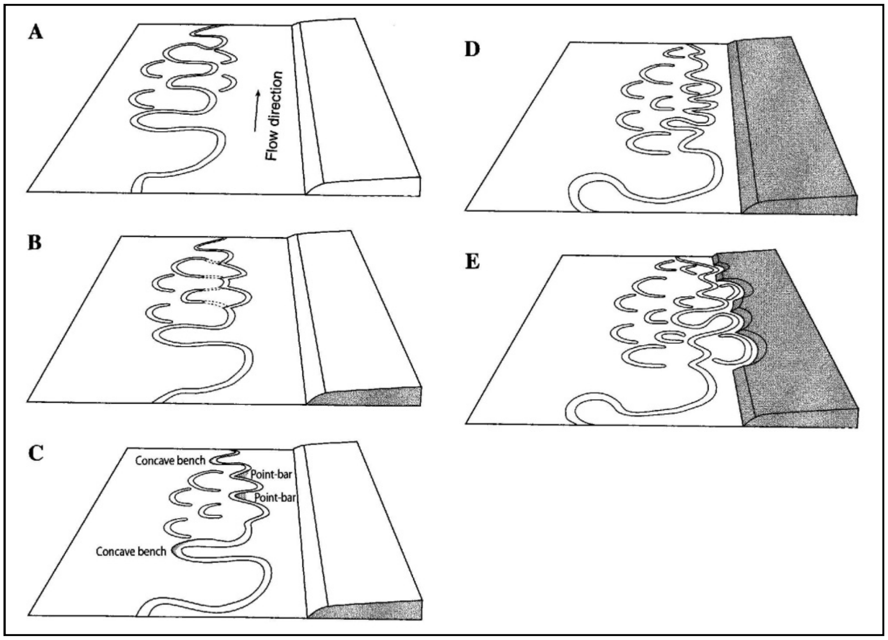
2.2.2 Controls

2.2.2.1 Climate versus Tectonics

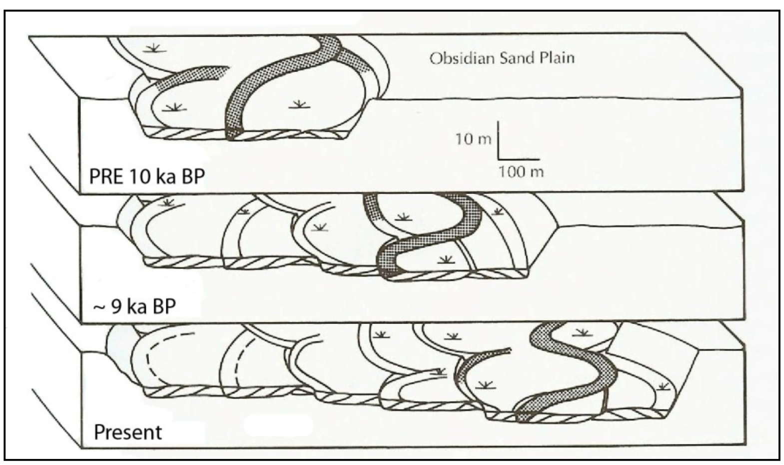
Climate can affect fluvial systems on scales of decades to hundreds or thousands of years while tectonic processes generally affect rivers on the scales of thousands to hundreds of thousands of years (Vandenberghe, 1995; Tebbens et al, 1999; Harvey, 2002). Vandenberghe (1995) and Tebbens et al (1999) add that climate can have affects on 100 ka timescales, but only within the confines of the tectonic framework of the area. In the century timeframe local thresholds such as increased precipitation, the duration and intensity of warm or cool periods, and sedimentary thresholds are most striking.

Bridge (2003) says there is not enough evidence that climate strongly affects geometry of river channels because modern rivers of varying size and channel patterns occur in all climatic zones. Certain changes, such as increased vegetation, in warming climates would not affect fluvial systems or channel pattern while other factors like increased precipitation and sediment transport could force a river to change from a meandering to a braided system. Bridge adds that large woody debris would affect channel pattern. However, Veldkamp and Kroonenberg (1993), Reugg (1993) and Veldkamp and Tebbens (2001) say that warmer periods would increase evapotranspiration and would encourage rivers to change from braiding to meandering as more plants increased bank stability. Alternately, a cooler climate would inhibit plant propagation and decrease evapotranspiration thus increasing surface runoff.

Tectonics affect the slope directly and the supply of water and sediment into rivers and floodplains indirectly. On a larger scale, a whole river system may be affected by tectonic activity over thousands to hundreds of thousands of year (Bridge,2003). Isostatic rebound owing to glacial retreat can affect regions on scales of thousands to tens of thousands of years. The last advance of the Laurentide Ice Sheet during the Late Wisconsinan and Holocene reached as far south as Iowa and South Dakota (Dyke and Prest, 1987; Forman and Pierson, 2002) at around 15 to 18 ka before it started retreating north. Larger scale tectonics can involve tilting of an entire river valley, which can cause the shifting over a river system laterally across a valley floor (Leeder & Alexander, 1987; Holbrook, 1999; Bridge 2003) (Figure 2.7). Valley tilting can also result in a longitudinal change of slope along a river's length. Alabyan and Chalov (1998) discuss the importance of stream power on channel development and slope. Excessive stream power is spent on lateral bed erosion. Bed erosion incises and lateral erosion expands valley floor width or channel belt width in an unconfined valley. Changes in slope along a valley can determine whether a river shifts from braiding to meandering to compensate for slope change.



(a)



(b)

Figure 2.7: Lateral channel migration due to lateral tilting (a) lateral tilting illustrated by Peakall et al, 2000, (b) Lateral tilting illustrated by Bridge, 2003. Note: Concave surfaces of meander bends all face the same direction.

While tectonics generally affects fluvial systems in the 100k year range, sudden tectonic shifts can force changes over much shorter time intervals. Frequent or periodic tectonic activity of faults in a river system or valley can result in local change in valley slope, river diversion and channel pattern change on a scale of hundreds or thousands of years. Local tectonic movements include relatively small faults and folds that directly influence topography and slope. The Reelfoot Rift in the New Madrid Seismic Zone is a good example of local period tectonic activity (Guccione et al, 2002; Hoolbrook et al, 2006). The Reelfoot Fault is an example of a sudden tectonic change. The fault movements in the New Madrid Seismic zone forced local changes in the Mississippi River that required decades to centuries for the river to adjust.

2.2.2.2 Bank Stability

A river's ability to migrate across a valley floor is restricted by the strength of the channel bank material through which the river is flowing. The weaker and, consequently, more easily erodible the bank material, the easier it is for rivers to migrate laterally across the valley floor. Conversely, the more cohesive the bank material, the more resistant it is to erosion restricting channel migration. Constatine et al's (2009) study of bank composition and erosion showed that alluvial terraces were the most resistant to erosion, after bedrock, and that terraces can be cemented so well that erosion is practically zero. The next most resistant bank types were banks with a gravel base, followed by banks dominated by roughly 90% clay material. Sandy banks were by far more susceptible to erosion being almost 10 times more erosive than terrace deposits. Hooke (2007a and 2008) also found that stable meander bends were attributed to low gradient and resistant banks such as thick clay cut banks and bends butted up against higher terraces.

Workers have conducted laboratory flume experiments trying to simulate stable meandering systems (reviewed in Tal and Paola, 2010). Friedkin (1945) was successful in simulating quasistable single channel systems, but if the lab experiment ran long enough these would become multichannel and braided. Jin and Schumm (1986) experimentally created a meandering system made of erodible sand substrate capped by a cohesive layer of fine sand and clay, but the channel bed could not be replenished with new sediment and as a result was not self-maintaining. Smith (1998) produced a high-amplitude sinuous meandering system using cohesive banks composed of kaolinite, cornstarch, white China clay and diatomaceous earth, but the main downfall was that the channel eventually reached a state of equilibrium and no longer migrated and also generated no chute cutoffs. Peakall et al (2007) were able to produce meandering with their experiments using a combination of sand and silica flour. Meander development started upstream and propagated downstream. The combination of sand and silica flour increased the cohesiveness of the banks. Fine material settled out of suspension building higher point bars and filling in chute-channels preventing flows from splitting.

2.2.2.3 Vegetation and Bank Stability

Vegetation is also a contributing factor in bank stability. Given enough time and proper conditions to develop, vegetation helps stabilize cut banks and bar surfaces (Hadley, 1961; Brice, 1964; Smith, 1976; Witt, 1985; Fielding et al, 1997; Huang and Nanson, 1997; Millar and Quick, 1998; Rowntree and Dollar, 1999; Gran and Paola, 2001; for review Bridge, 2003). Brice (1974) states that higher sinuosity rivers seem to be the most heavily vegetated and contain no cutoffs. Camporeale et al's (2007) modeling of river meandering also shows the effect of vegetation on bank stability and enhancing resistance to erosion. Hooke (2008) studied the River Dane and showed that low discharge levels and thus lower flow allowed vegetation to spread further down channel banks and increased bank stability. This increased stability would eventually go away if flow levels increased and were maintained for extended periods. While riparian vegetation will increase bank stability, trees would decrease stability owing to their wider spacing; the shade of the trees would also limit plants on the banks to shade friendly species resulting in a less densely vegetated bank (Thorne and Osman, 1988).

Laboratory experiments were conducted by Braudick et al (2009) and Tal and Paola (2010) to observe the effects of vegetation on bank stability and channel sinuosity. Braudick et al (2009) seeded alfalfa sprouts in non-cohesive sediment of varying sizes. They found that varying the water discharge rate, but not exceeding near bank full capacity was sufficient to force channel migration and maintain a meandering channel throughout the experiment. Braudick's simulated river did develop a number of chute channels (discussed later) and determined had they more densely seeded the alfalfa sprouts fewer chutes would have developed.

Tal and Paola (2010) ran two lab experiments to study the effects of vegetation on channel morphodynamics. They used a well sorted material to simulate non-cohesive (sandy) sediment, planted alfalfa sprouts on the banks to simulate vegetation and simulated flooding periods at regular intervals. There was no continuous sediment supply, so the experimental rivers were limited to the sediment with which they started. They observed that the vegetation stabilized the banks during low to medium flow periods. The vegetation reduced the number of cutoffs, but they were more predictable. They concluded that plants alone are able to achieve two key mechanisms in laboratory experiments that can translate to natural rivers: 1) slowing the rate of widening thus keeping erosion and deposition relatively in sync and 2) discourage channel cutoffs influencing increased river sinuosity.

2.2.2.4 Large Woody Debris

While banks populated by tree growth might decrease bank stability, large woody debris of collapsed trees caused by flooding or erosion of cut banks can disrupt the flow structure of a river (Daniels and Rhoads, 2003). The large woody debris creates a partial, or complete, barrier that redirects water flow around or over the obstruction (Figure 2.8). The obstruction, therefore, modifies the flow, sediment transport, patterns of erosion and deposition, and, potentially, channel development. Elliot and Jacobson's (2006) report on the Missouri River states that Large Woody Debris obstructions are a common element of the Missouri River.

2.2.2.5 Erosion and Deposition

River banks are involved in a constant state of erosion and deposition. The outer banks of channel bends are constantly being eroded as the increased stress of channel flow is applied against them. At the same time, sediment is deposited in areas along the channel where flow and shear stress are the weakest, generally in the inner banks of river meanders or island bars of braided rivers. Even though river banks composed of cohesive silts and clays and covered with vegetation are highly resistant to erosion at bank full discharge; they are still susceptible to erosion and allow river migration (Anderson et al, 1975). Clay cut banks are weakened by water discharge and fail in blocks (Thorne and Osman, 1988; Osman and Thorne, 1988; Lauer and Parker, 2008), which in turn armors the channel cut bank slowing erosion.

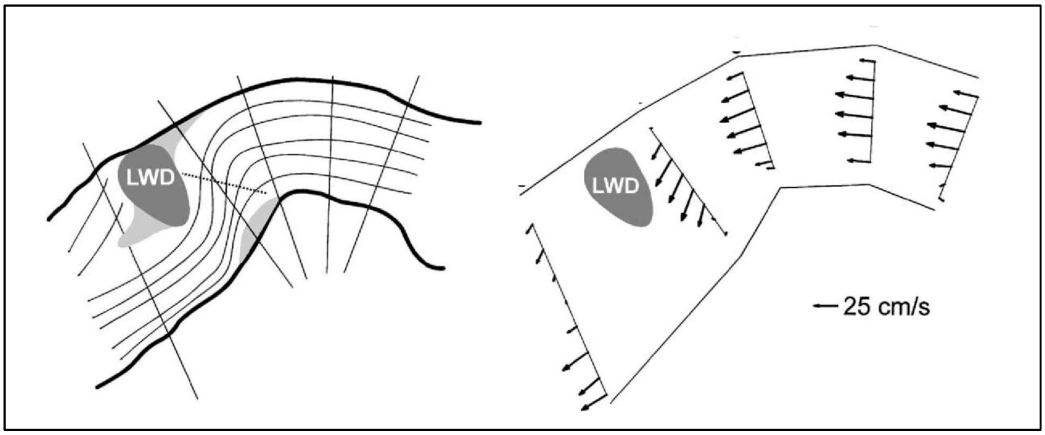


Figure 2.8: Water flow diverts around Large Woody Debris obstruction (Madden Creek, Illinois). Shading indicates stagnating flow. (Modified from Daniels and Rhoads, 2003)

Parker et al’s (2010) modeling of meander river migrations observed that stability on the inner bank of a meander bend required additional assistance to help stabilize it and preventing it from cutoffs or from transitioning to a braided system. Sediment suitable for vegetation would be deposited stabilizing the inner bank, which has the effect of trapping more sediment. This would encourage increased water flow diversion to the outer bank increasing erosion. Depending on the amount of cohesive or non-cohesive sediment on the outer bank, erosion could be very fast, average or slow. Parker et al (2010) concludes that the more cohesive the sediment, the slower the erosion process. Earlier modeling conducted by Thorne and Osman (1988) implies that cohesive banks add sediment to a river more slowly than non-cohesive banks. Cohesive banks fail and add sediment to a river in blocks owing to weakness or unusual discharge, but sand or gravel banks are always in a state of erosion.

While clays are resistant to stream migration, non-cohesive sediment (e.g. sand) is easily the most susceptible to the erosive capacity of fluid flow (Anderson et al, 1975; Constatine et al, 2009). In an effort to remain at a constant width, water flow down a channel erodes/cuts into the outer bank widening the channel, the river deposits sediment on the inner bend to maintain equilibrium. If the channel widens in a particular reach, deposition will increase due to weaker flow strength. Conversely, if a channel becomes narrower along a channel reach, the resulting decrease in hydraulic radius and thus increased discharge will favor erosion until flow strength can reach a stable state. Observations by Jackson (1975) reported that mean grain size of sediment increased in meander loops that narrowed because of the increased local velocity in the channel. The mean grain size would decrease once the channel widened back outside the loop.

Anderson et al (1975) conducted a series of laboratory experiments trying to replicate characteristics of morphology of meandering and braided channels. He observed that major morphological changes only occurred between medium to bank full discharge, but there was practically no change at all during periods of low discharge. However, Parker (1976) modeled the characteristics of braiding and meandering rivers and implies that during periods of low flow in braided rivers owing to the effects of bed topography and resulting weaker flows in some parts of the river bed, sand bars can develop.

2.2.2.6 Helical and Secondary Flow

Helical flow occurs along meander bends and involves the corkscrew motion of water as it travels from one meander bend of a channel to the next. As water enters a river bend, it doesn't follow the center of the channel, but instead momentum pushes it towards the outer bend of the channel. The water flow reaches the outer bend; it is pushed downward towards the bottom of the channel cutting into the outer bank of the river bend and eventually spirals toward the inner bank of the bend where the water can deposit sediment on the inner bank of the channel. This pattern is repeated as the water flow exits one meander loop and enters the next one (Figure 2.9).

In an effort to remain at a constant width, water flows down a channel eroding or cutting into the outer bank widening the channel, the river deposits sediment on the inner bend to maintain equilibrium. If the channel widens in a particular reach, deposition will increase due to weaker flow strength. Conversely, if a channel becomes narrower along a channel reach, the resulting decrease in hydraulic radius and thus increased discharge will favor erosion until flow strength can reach a stable state (review see Bridge, 2003). Several studies agree (Mosonyi et al – 1975; Yen – 1975, Jackson – 1975 and Carson and Lapointe – 1983) that water flow around meander bends becomes helical very fast and causes the greatest amount of erosion initially, but as it continues around the bend the strength of the helical motion slowly decreases. Jackson's (1975) studies showed that the intensity of helical flow increased in deeper channel loops.

Water doesn't flow as one unit, but is affected by the shape and geometry (i.e. curvature, obstructions, friction) of the channel down which it is flowing. The spatial or topographic variations in the river channel can affect the flow direction of water resulting in secondary flows that cannot be disregarded as insignificant. Brathurst et al (1977) studied the water currents on the outer banks of some meander bends in the Upper River Severn. Depending on the shape and strength of water flow on the outer bank, the existence or strength of the secondary flows varied. On meander bends where the outer bank sloped or shelved up to the surface, no secondary flows were detected, but on meander bends where the outer bank was a vertical cut bank wall, secondary flows were present. Included with the downward cycling of the helical flow around the meander bender, near the surface there was a reverse, upward secondary current present. The secondary current was stronger in bends where there was an increased water flow against the outer bank caused by obstructions in the channel bed forcing increased flow against the outer bank (Figure 2.10a).

Later, Thorne and Hey (1979) moved to study the presence of secondary flows at the inflection point between meander bends. They measured water flow at three points near the inflection of two meander bends (Figure 2.10c): 1) near the exit of a meander bend, 2) at the inflection point between two meander bends and 3) at the entrance of the next meander. Thorne and Hey (1979) found that at the exit of the first meandering loop, there was only one cell which was the helical flow to the outer bank near the water surface with the flow coming back to the inner bank underneath. At the entrance to the next meander bend, the flow cell had completely shifted and was now flowing to the outer bank of the new meander bend. At the inflection point, however, they were able to measure two stacked flow cells: on top) the diminishing flow cell from the last meander loop heading to the now missing outer bend; on the bottom) the newly forming flow cell flowing to the outer bend of the upcoming outer bend on the opposite bank. Flume experiments using a flume with a uniform bottom (Chacinski and Francis, 1952) showed that the flow cell from the previous meander persisted well into the next meandering bend, yet in a natural river the flow cell from the first meander bend was completely gone by at the entrance to the new meander bend. Thorne and Hey (1979), later recognized by Bridge and Jarvis (1982) and reviewed in Bridge (2003), concluded that the non-uniform bottom of the river, mainly the presence of the thalweg as it migrated from the outside of the first meander bend to the opposite bank of the upcoming second meander bend, was the cause of the 2 cell flows at the inflection and the complete absence of the first flow by the time the water flow entered the next meander loop.

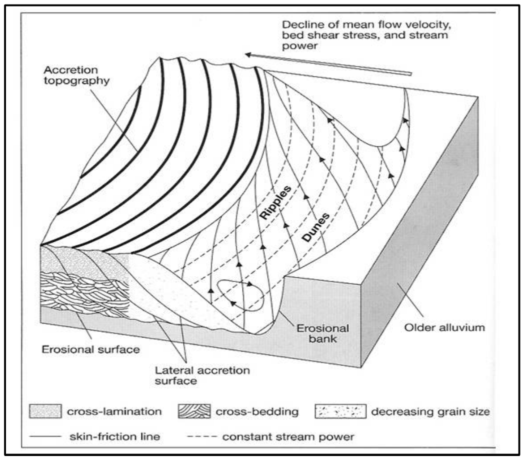


Figure 2.9: Helical Flow around a meander bend. (Leeder, 1999)

Thorne et al (1985) published another study concerning secondary flows, but this time they focused on the presence of secondary flows on the inner banks of meander bends. They focused on the effects of helical flows and secondary flows on the inner bank of a sandy-bed river and the presence of one or the other at different discharge levels (Figure 2.10b). The helical flow should push sediment from the outer bank along the bed and deposit on the inner bank of the bend further downstream. An outward secondary flow radiating from the bank pushing outwards across the entire depth about the point bar would indicate that the helical flow is confined to the deepest part of the river around the thalweg. Bridge (1977) and Dietrich and Smith (1983) suggests this would be the case under 2/3 bank full flow. At intermediate flows, the data agreed with predictions by Bridge (1977) and Dietrich (1983). A radial secondary flow pushed outwards from the inner bank confining the helical flow. However at bank full flow, Thorne's results were different. Upstream, at the head of meander bends, the helical flow was strong enough to scour the point bar and push sediment up the inner bank. Downstream, at the lower part of the bend, the secondary flow continued to radiate out from the inner bank owing to the widening of the channel down bend, however, the point bar is more prominent downstream from accretion than it is upstream due to the scouring effect.

Ferguson et al (2003) also looked at secondary currents on inner river banks. Though their research mainly focused on comparing water flow separating from the inner banks of meander bends of differing sharpness, they did find that that the secondary flows and mild bed topography differences could force the maximum strength of the helical flow around the meander to reach the outer bank of the river bend upstream of the bend apex rather than at or downstream of the apex. Ferguson et al (2003) acknowledges this could have implications on bank erosion and meander migration (Figure 2.11).

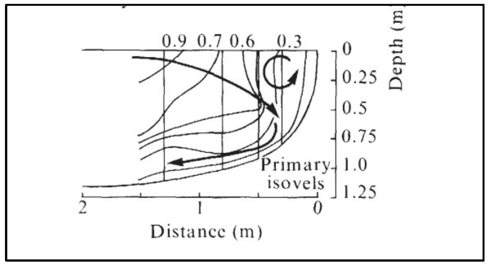
Leeder and Bridges (1975) research indicates that in tight meander bends, instead of a helical flow, water flow can separate from the inner bank; the tighter the bend, the greater the separation. The effect of the flow separation was the decrease in effective width downstream and a greatly increased local water velocity and sheer strength against the outer bank encouraging higher erosion rates (Jackson, 1975; Leeder and Bridges, 1975). This increased velocity against the outer bank will simultaneously reduce flow strength along the inner bank producing eddies and vortices greatly increasing deposition along the inside.

2.2.2.7 Channel Cutoffs and Channel Fill

Much research has been applied to the study of channel cutoffs. There are two recognized forms of cutoffs in rivers: neck cutoffs and chute cutoffs. Neck cutoffs occur when two meander bends in a river meet allowing water flow to bypass the previous channel route effectively severing it and thus reducing the river's length and sinuosity (Figure 2.12). The two arms of the severed channel length are plugged up by the sediment load of the river producing oxbow lakes which becomes a sediment sink and part of the topography of the river valley. While neck cutoffs reduce channel sinuosity, chute cutoffs limit river sinuosity (2.13). Chute formations exhibit some common characteristics. The presence and frequency of chute cutoffs can be linked to bank stability, and often occur during periods of flooding where water discharge and the capacity to entrain sediment increase. Chutes often form along a river where the curvature of the channel is the greatest, usually within swales with low vegetation (Camporeale et al, 2008), escaping from the main channel where riverbanks most strongly turn away from the downstream flow path. They are often roughly parallel to the directional flow of the river.

Constatine et al (2010) studies various empirical and theoretical observations of the Sacramento River and the previous works of others (California Department of Water Resources, 1979; Singer and Dunne, 2004). They recognize at least three primary controls on the occurrence of chute cutoffs by embayment and extension, 1) Valley slope, 2) structure of the floodplain and 3) the nature and quantity of sediment transported during a flood. First, valley slope impacts the rate water flow travels down slope; the greater the slope, the faster water travels down the valley slope. Second is the structure of the flood plain. If vegetation is dense enough, river banks can resist the erosion process and chutes cannot occur since cutoff is the only method of shortening; vegetation enables river channels to evolve and become more highly sinuous. Trees would increase chute cutoffs since they are spaced far enough apart and only smaller, shade friend plants could thrive, thus, effectively weakening bank strength. Third is the nature and quantity of sediment transported during a flood. During periods of low sediment volume in a river, there were more frequent chute cutoffs along the Sacramento River because the river had the capacity to carry more sediment; however, along river stretches of high sediment volume, chute cutoffs were less frequent (Singer and Dunne, 2001). Streams already at capacity lack the capability to form chute cutoffs unless there is a blockage that encourages it. If sediment supply rate is increased beyond the sediment capacity of a river, aggradation will occur as the stream dumps its sediment load. Once the sediment supply rate is reduced below the sediment capacity of the river, then degradation will increase also increasing the potential for chute channels (Smith and Smith, 1984; Ashmore, 1991; Hoey and Sutherland, 1991, Germanowski and Schumm, 1993; Bridge, 2003).

Brice (1974) implies that cutoffs upstream can cause a number of changes downstream such as increasing sinuosity downstream. Bridge et al (1986) notes that a change upstream, say a chute cutoff, could cause increased migration downstream and that it could take decades or more for the river to adjust downstream. An upstream cutoff would increase water discharge downstream and increase erosion and therefore increased meandering to compensate to slow the water down again, but not necessarily enough of an increase in discharge that could cause further cutoffs.



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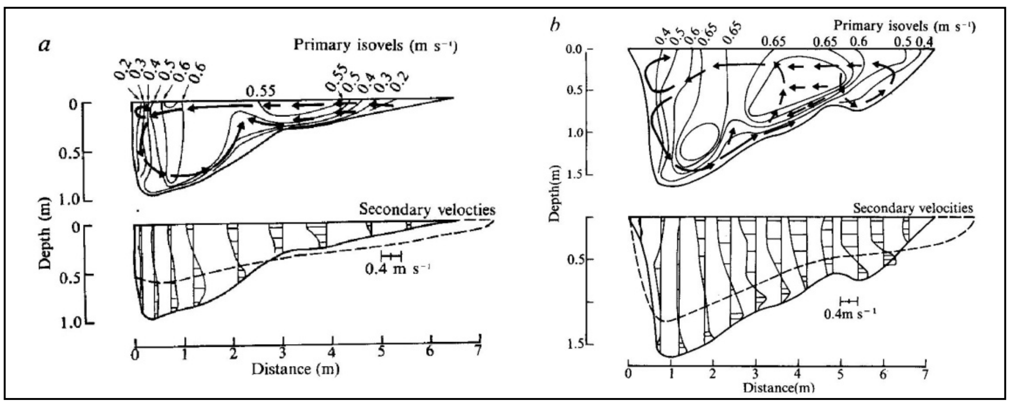

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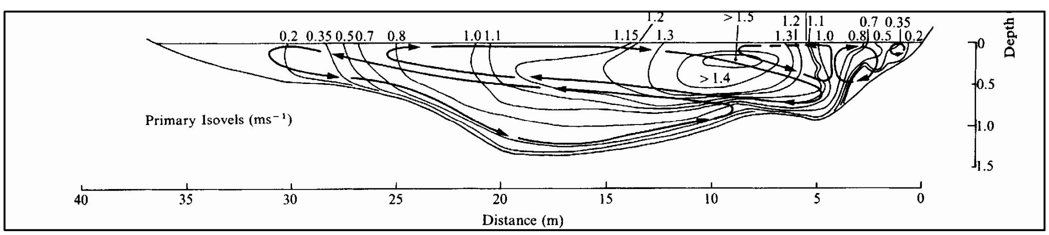


(c)

Figure 2.10: Secondary flows at different stages of a meander bend (a) upward secondary current at apex of bend cut bank, (b) Secondary flows at apex of inner bank bend, (c) Stacked flow helical and secondary flow cells at meander inflection. (a: Brathurst et al, 1977), (b: Thorn and Hey, 1979), (c: Thorne et al, 1985).

However, more recent studies by Stolum (1996, 1998) propose that the meandering process of freely meandering rivers oscillates between a river morphology that is ordered and one that is chaotic. Freely meandering rivers can eventually reach a super critical state becoming so sinuous that the river will eventually undergo a series of cutoffs undergoing a self-organization process transitioning back to a more ordered, less sinuous state. Rivers reaching a sinuosity of a mean of 3.14 based on the equation:

S (*Sinuosity Ratio*) = **L** (*Distances measured between two points along a stream*) / **l** (*Straight line distance between two points*)

is a critical state and channel sinuosity beyond that being a super critical state. Stolum (1996, 1998) models the long-term behavior of freely meandering rivers and compares his simulations to satellite imagery of stretches of river. Since large rivers develop so slowly, he limits the comparisons to smaller tributaries in the Amazon Basin. Stolum's work also showed the ability of freely meandering rivers to become highly sinuous even to the point of loops turning up-dip against the slope of the valley. Hooke's (2003) observations of the River Bollin agrees with Stolum's (1996) conclusions, but adds the condition that river channels may continue to migrate at medium and possibly low flows, but the cutoffs will only occur during bank full or flooding episodes.

Once cutoffs are formed they will either fill back in with sediment or become the new route for the bulk of the river flow while the cutoff channel is filled in and plugged up by river sediment. If the angle between the active channel and the cutoff channel is small, a river's bed load will fill the channel entrance and then fining upwards as less water flow is able to enter. Further downstream of the cutoff entrance finer grained material and organic matter will settle out of the water owing to the slower moving waters. At larger angles of divergence between the active channel and cutoff channel, both ends of the abandoned channel are quickly blocked with fine grained sediment and organic matter will settle out of suspension in the ponded water (Bridge, 2003 for review). Hooke's (2008) studies of the River Bollin and Hudson and Kesel's (2000) studies of the Lower Mississippi river showed that cutoffs filled with gravel and sands filled quickly, but were weak thus susceptible to reoccupation. Cutoffs that were plugged with clays and silts would be more resistant to future channel migration.

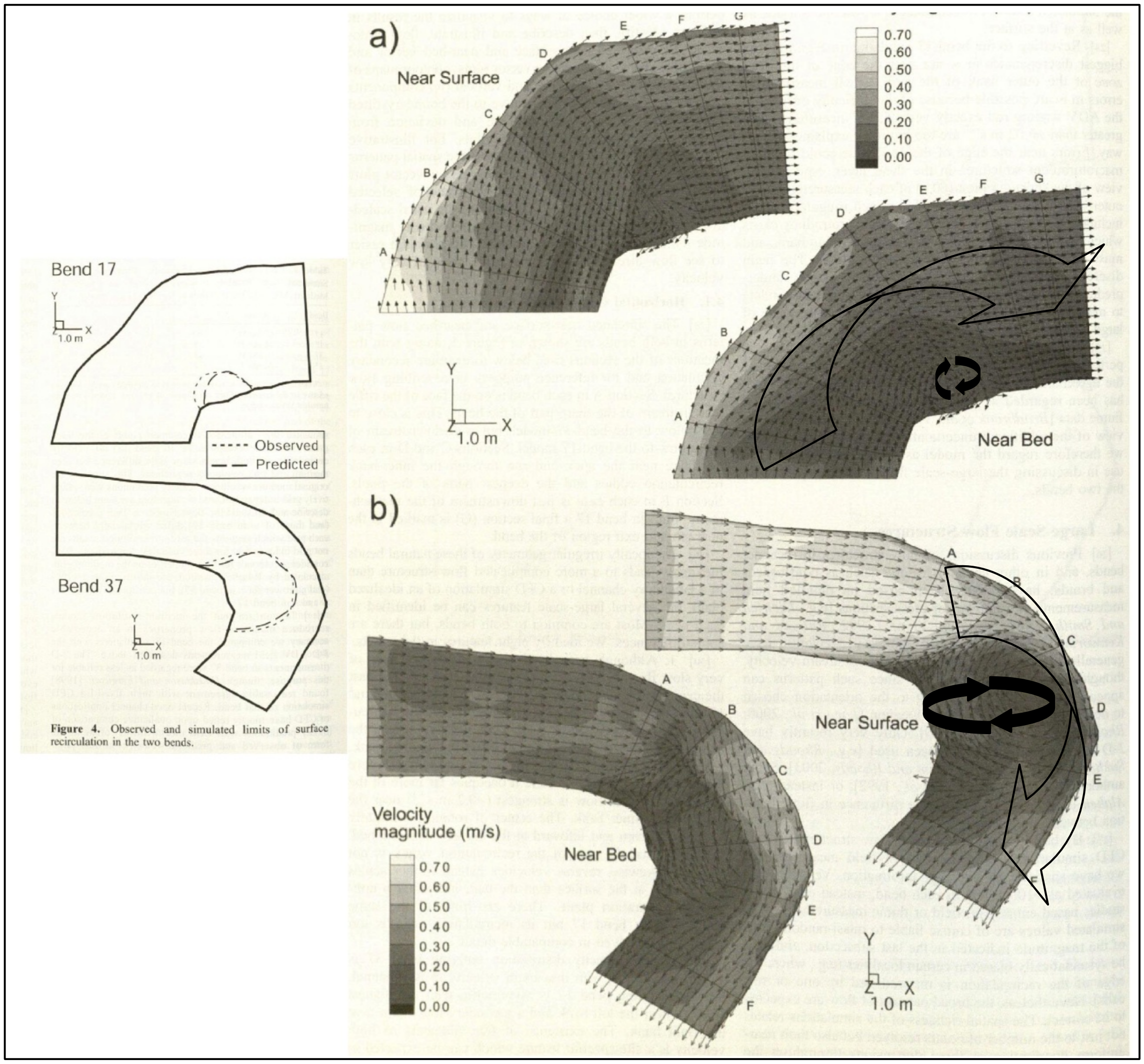


Figure 2.11: The sharper the bend, the greater the flow separation from the inner bank (Ferguson et al, 2003)

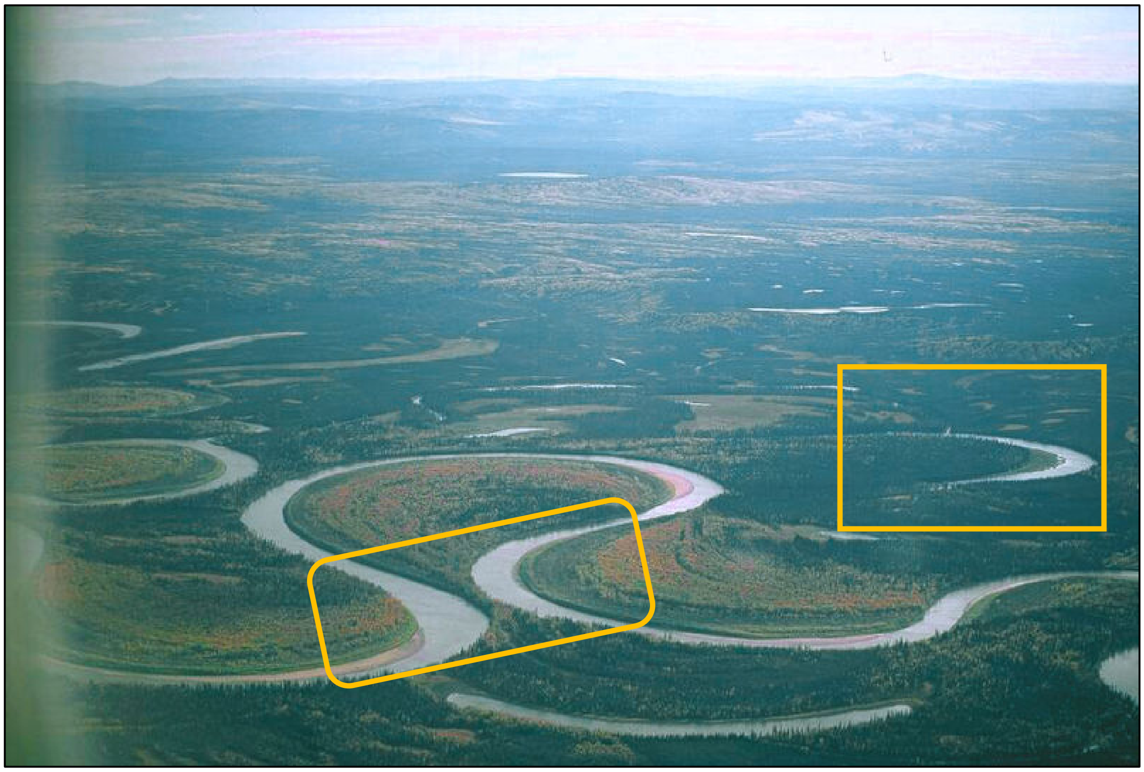


Figure 2.12: A neck cut off. This segment of the Nowitna River is close to undergoing a neck cutoff. The severed loop will develop into an oxbow lake and become a preserve allo-unit in the valley floor similar to the lake to the right of the loop.

Figure 2.13: A chute cut off. A chute in the Middle Mississippi National Wildlife Refuge forms a shorter path for water flow.

CHAPTER 3

METHODS AND DATA ACQUISITION

This goal of this study is to determine what conditions or processed involved in the initiation and development of the gooseneck loops in the study area. Mapping and chronological dating techniques were utilized to learn these answers. This study utilized a database established during the summers of 2009 and 2010 in conjunction with data collected during this project to augment this data base. Data consists of floodplain field maps completed in the Missouri River floodplain over the reach extending from Sioux City to Tyson's Bend Iowa (Figure 3.1). Mapping, drilling and sample data collection each of the two summers was performed by five teams of 2 undergraduate students each linked to an NSF-REU project and one team of two graduate students linked to a USGS EDMAP project, both with Dr. Holbrook as supervising PI. Mapping areas are split between the groups by quadrangles. The 2010 field groups mapped quadrangles from Tekamah NW, Nebraska south to Mondamin, Iowa-Nebraska, of which Mondamin was mapped by University of Texas at Arlington graduate students Michele Kashouh and Daniel Carlin. The goal of both NSF and EDMAP projects is to perform detailed surface Quaternary alluvial mapping of the Missouri River Valley. Mapping procedures consisted of delineation and dating of allostratigraphic floodplain units. Allostratigraphy is the mapping of units based on recognition and delineation of their bounding discontinuities (NACSN, 1983).

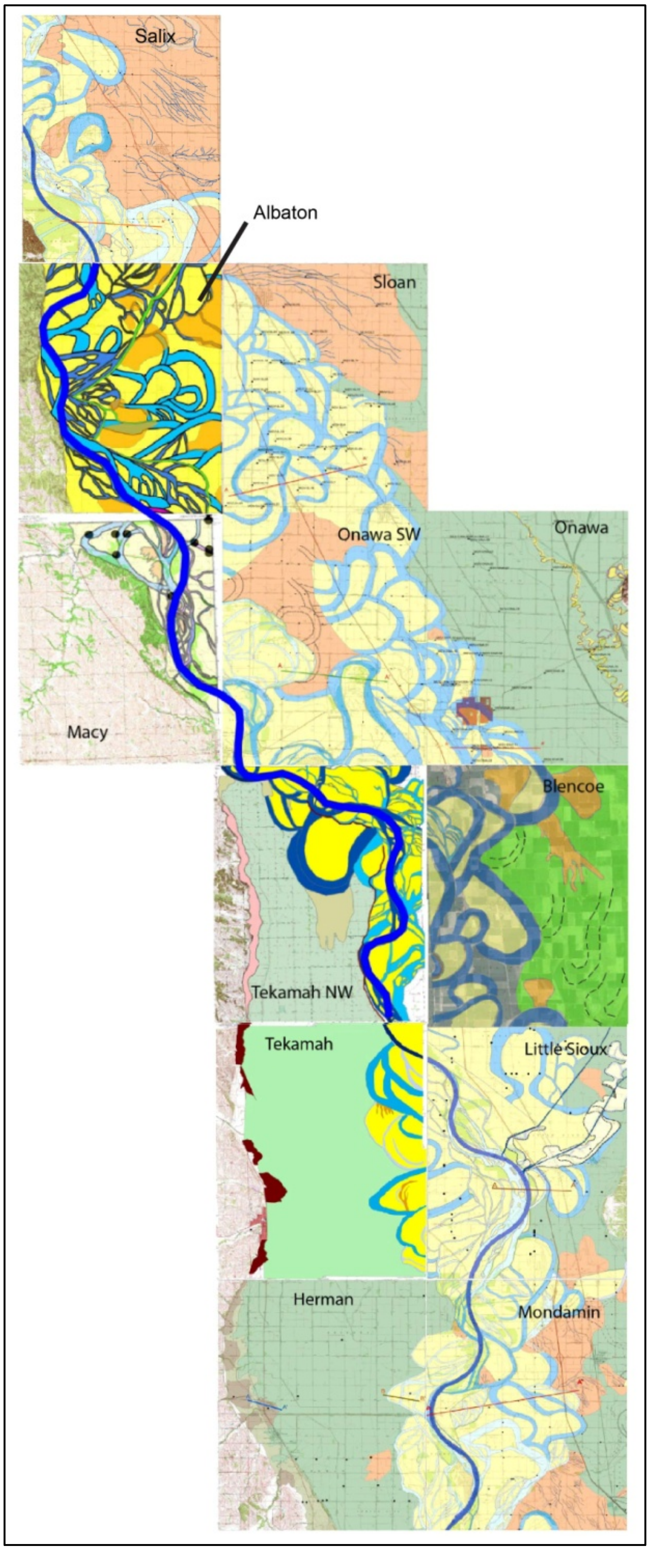


Figure 3.1: Allostratigraphic maps from Salix Quadrangle, IA to Mondamin Quandrangle, IA.

Mapping initiated in the target reach by analyzing topographic maps, aerial photography, and digital elevation models (DEM) and existing soil maps to recognize landforms characteristic of likely depositional units and trends. We assessed the likely allostratigraphic mapping units within the valley alluvium using our observations in conjunction with already established architectural models (e.g. Miall 1996). Allostratigraphic units identified and mapped were discrete architectural elements including ox-bow/channel fills, point bars, and splays, as well as larger composite units of back swamp, terrace fragments, and channel belts of smaller floodplain streams. The landforms and depositional units were drawn onto topographic maps creating a series of “hypothesis maps” to illustrate the proposed allostratigraphy of the targeted areas.

Development of hypothesis maps was followed by field testing using hand-auger drilling (Figure 3.2). For example, a topographic ridge inside an arced topographic trough might be inferred as the terminus of a point bar inside an abandoned meander channel/ox-bow fill. It would stand to reason that drilling there would reveal sandy or mostly sandy strata with the possible occasion of mud drapes. Alternatively, drilling within the adjacent trough would reveal mostly muddy channel-fill strata. Drilling would confirm or falsify these predictions based on the lithology from the auger cores. If the prediction fails, then the hypothesis is falsified then a new hypothesis needs to be formed. Eventually, the mapping of the area via this procedure results in a prepared final map of the allounits and their lithologic characteristics within the target area.

Age dating of targeted loops follows after the mapping. Some of these more specifically target determination of the ages of the goose neck meander channels that are the focuses of this study. Relative ages of channel meanders and other landforms can be determined by direct observations from completed maps. For instance, channel meander 1 is a wide turning loop that cuts across the inside of a tighter hairpin meander 2. Both channel arms of channel 2 end into channel 1. We can safely assume that Channel 1 is younger than 2 and never completely scoured away channel 1 (Figure 3.3). Numerical dates were assessed using optically stimulated luminescence (OSL) on sand samples collected from point bar allounits (Rodnight et al, 2005). Sites for OSL testing are selected after preliminary mapping. OSL locations are chosen based on the growth pattern of the meander (Figure 3.4).

Gooseneck meander loops are present in several of the quadrangles mapped over the 2009 and previous years with further locations in the 2010 map area. These maps will be used to identify gooseneck meanders for this study. I will then use the aerial photos to follow traces of the meander scrolls within the individual loops to determine growth patterns and trajectories of the meanders and the relationship to other valley features. This will also serve as a guide to determine where to best take soil samples for OSL dating, it also allows us to track and determine how and in which directions the meanders evolved over time.

(a)

(b)

Figure 3.2: The Dutch Auger System (a) images of drilling with an auger set, (b) illustration of soil samples. Boreholes can reach up to 10 meters deep; core samples are drilled in 10 cm increments.

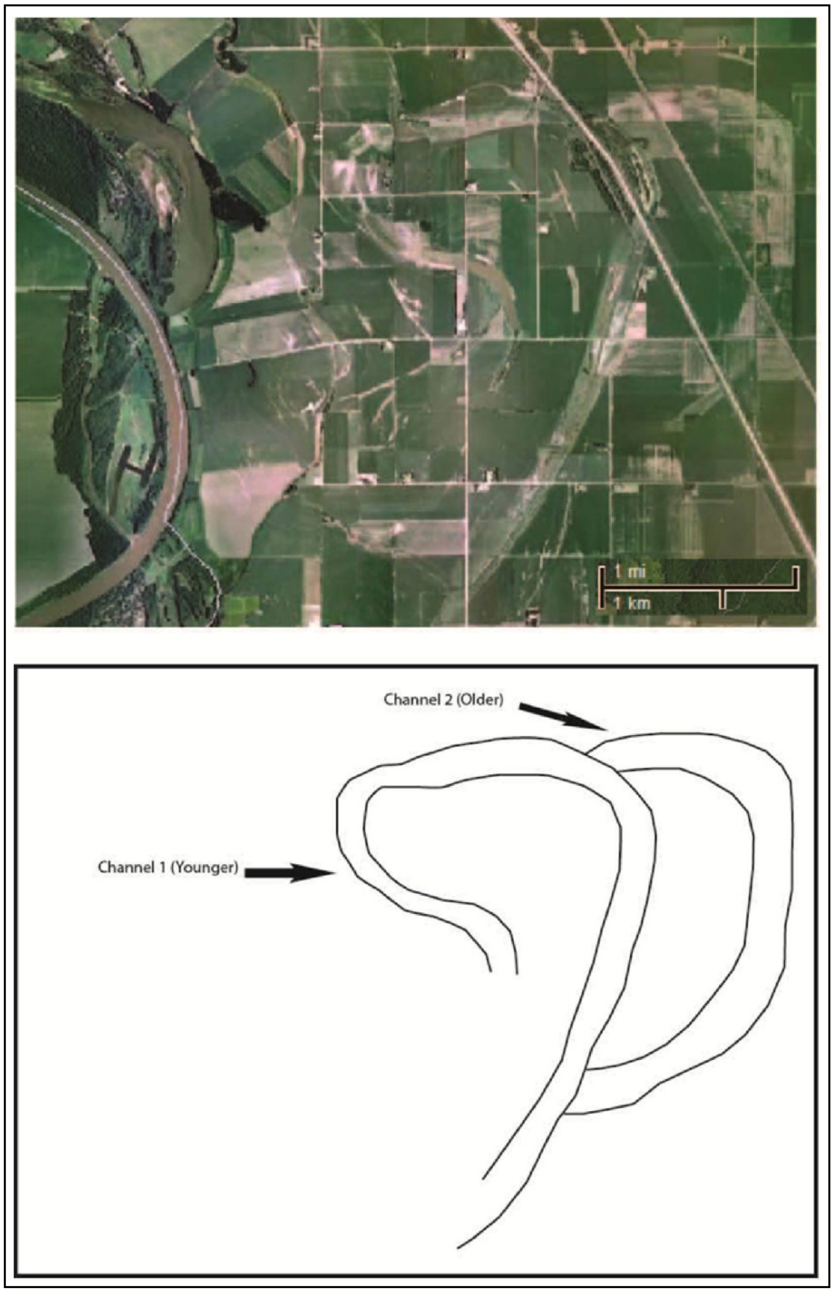


Figure 3.3: Older channel versus younger channel.

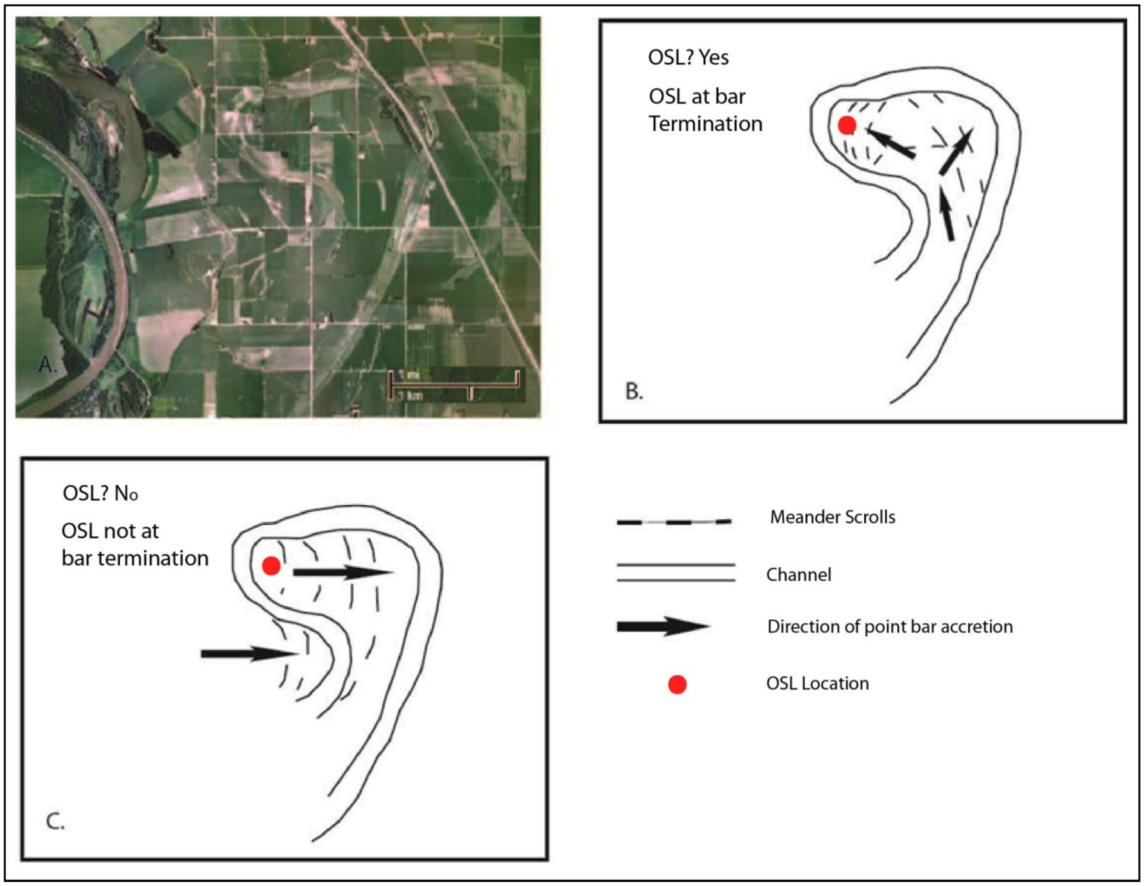


Figure 3.4: Determining the best locations for collecting OSL samples. Using meander scroll patterns, B would be a good location if trying to date bar termination.

CHAPTER 4

RESULTS

4.1 Results

The field data gathered for this research will be presented in order of the year it was collected starting in 2009 to 2010 and also starting with the furthest North quadrangle, Salix IA, progressing south to Mondamin, IA-NE (Figure 3.1). The complete map versions for each quadrangle discussed in this section are compiled in Appendix 1. The observations and data will cover full maps of the locations of focus, the growth trajectories of point bar accretion based on scrolls, and the alluvial composition of the bore holes drilled inside and around the meander loops.

Locations of OSL dating are included with the appropriate quadrangle. For the sake of clarity, OSL sample names are designated by the name of the hole. So if a borehole was drilled in Mondamin and called MOV-MD-10 and an OSL sample was collected from this hole then the OSL sample will be called the same name MOV-MD-10. All OSL data for samples collected and used in the study are reported in Table 4.1 and 4.2. Please note that three OSL samples were collected during the summer 2010 field work that are located in the 2009 field area because it was deemed necessary for additional information. These are included and discussed with their appropriate quadrangles.

The sediment logs containing sediment composition data of the pertinent drill holes discussed in this study are included in Appendix 2. The remaining logs from 2009 and 2010 maps not specifically discussed in this study will be available, with their appropriate map publications (*Currently in Review*), as well as those used in this study, in the near future via the South Dakota University Press.

The following collected data are presented for each gooseneck location by quadrangle: 1) Gooseneck location, dimensions and channel length, 2) locations, dates and specific information pertaining to OSL samples, 3) scroll patterns pertaining to the gooseneck, and 4) soil composition of relevant drill holes pertaining to the gooseneck.

Table 4.1: OSL data collected during 2009 project year.

Missouri R., Nebraska

UNL #	Field #	Burial Depth (m)	H_2O (%)*	K_2O (%)	±	U (ppm)	±	Th (ppm)	±	Cosmic (Gy)	Dose Rate (Gy/ka)	D_e (Gy)	No. of Aliquots	Age (ka)	Model
UNL2490	MOV-AL-12	1.6-1.9	17.1	2.18	0.06	3.51	0.14	8.10	0.33	0.17	2.82±0.12	2.84±0.25	34	1.01±0.10	CAM
												1.94±0.07	34	0.69±0.04	**MAM**
UNL2491	MOV-SL-45	2.25-2.45	21.9	1.90	0.05	1.66	0.09	4.26	0.24	0.16	1.93±0.09	14.05±0.47	31	7.29±0.48	CAM
UNL2492	MOV-SL-47	1.5-1.65	21.5	2.14	0.06	1.62	0.09	4.67	0.26	0.18	2.12±0.10	13.90±0.27	32	6.56±0.39	CAM
UNL2493	MOV-ONA-33	3.2-3.35	34.2	2.15	0.06	3.37	0.14	7.57	0.32	0.14	2.32±0.14	10.86±0.47	29	4.68±0.37	CAM
UNL2494	MOV-OSW-5	1.1-1.4	24.9	1.74	0.05	1.41	0.08	3.46	0.20	0.19	1.70±0.09	2.65±0.14	35	1.56±0.12	CAM
UNL2495	MOV-OSW-12	0.9-1.2	5.9	1.61	0.05	4.03	0.15	13.99	0.39	0.19	3.26±0.11	1.91±0.15	43	0.59±0.05	CAM
												1.21±0.03	43	0.37±0.02	**MAM**
UNL2496	MOU-LSY-50	4.0-4.25	25.8	1.89	0.05	2.25	0.10	6.09	0.25	0.13	2.03±0.10	24.92±0.27	44	12.2±0.7	CAM
UNL2497	MOV-OSW-58	0.7-1.0	16.5	2.13	0.06	3.69	0.14	4.69	0.26	0.20	2.66±0.11	1.80±0.15	37	0.68±0.06	CAM
												0.86±0.10	37	0.32±0.04	**MAM**
UNL2498	SSC-138	2.4-2.65	7.7	1.73	0.05	1.46	0.14	7.43	0.33	0.16	2.26±0.08	1.52±0.19	37	0.67±0.09	CAM
												0.85±0.07	37	0.38±0.04	**MAM**
UNL2499	MOV-AL-39	2.6-2.8	8.8	2.21	0.06	3.10	0.13	4.44	0.25	0.15	2.75±0.10	4.90±0.24	27	1.78±0.12	CAM
UNL2500	SSC-137	1.4-1.6	4.6	1.95	0.03	3.08	0.20	4.84	0.30	0.18	2.73±0.09	1.46±0.12	47	0.46±0.06	CAM
												0.80±0.09	47	0.29±0.04	**MAM**
UNL2501	MOV-SL-3	2.8-3.0	20.0	1.82	0.05	3.17	0.13	4.52	0.25	0.15	2.21±0.10	14.56±0.50	41	6.59±0.42	CAM

* In-situ Moisture Content
Error on De is 1 standard error
Error on age includes random and systematic errors calculated in quadrature

Table 4.2: OSL Data collected during 2010 project year.

UNL #	Field #	Burial Depth (m)	H_2O (%)*	K_2O (%)	±	U (ppm)	±	Th (ppm)	±	Cosmic (Gy)	Dose Rate (Gy/ka)	D_e (Gy)	No. of Aliquots	Age (ka)
UNL2818	MOV 53 BNC	4.7	22.8	1.67	0.05	1.23	0.09	3.89	0.20	0.12	1.63±0.08	3.22±0.12	51	1.98±0.13
UNL2819	MOV7 BNC	2.6	21.9	1.32	0.04	1.30	0.10	3.72	0.21	0.16	1.44±0.07	3.93±0.10	50	2.72±0.15
UNL2820	MOV-TWN-44	1.8	10.2	1.66	0.04	1.92	0.11	5.77	0.26	0.17	2.15±0.08	1.39±0.08	63	0.65±0.04
							Minimum Age Model (Galbraith et al. 1999) =					0.77±0.06	63	0.36±0.03
UNL2821	MOV-LS-34	1.5	20.3	1.59	0.04	0.83	0.08	1.95	0.17	0.18	1.47±0.07	2.78±0.10	55	1.89±0.11
							Minimum Age Model (Galbraith et al. 1999) =					1.90±0.40	55	1.29±0.28
UNL2822	MOV-BNC-54	0.7	8.2	1.77	0.05	1.60	0.10	5.23	0.27	0.20	2.21±0.08	2.62±0.04	50	1.19±0.05
UNL2823	MOV-TK-20	1.7	10.4	1.59	0.05	1.20	0.10	3.64	0.21	0.18	1.81±0.07	1.69±0.10	50	0.93±0.07
							Minimum Age Model (Galbraith et al. 1999) =					0.79±0.05	50	0.44±0.03
UNL2824	MOV-TK-25	2.1	13.0	1.52	0.04	1.07	0.08	4.21	0.22	0.17	1.71±0.07	1.35±0.07	61	0.79±0.05
							Minimum Age Model (Galbraith et al. 1999) =					0.58±0.20	61	0.34±0.12
UNL2825	MOV-LS-30	2.9	23.9	2.08	0.05	1.67	0.10	4.38	0.22	0.15	2.01±0.10	2.88±0.08	61	1.44±0.08
							Minimum Age Model (Galbraith et al. 1999) =					2.28±0.09	61	1.13±0.07
UNL2826	MOV-TK-44	3.7	20.8	1.78	0.04	1.46	0.09	4.06	0.21	0.14	1.80±0.09	3.53±0.06	62	1.95±0.10
UNL2827	MOV-SLX-57	1.1	6.4	1.59	0.04	1.16	0.09	3.90	0.21	0.19	1.91±0.07	0.82±0.04	66	0.43±0.03
							Minimum Age Model (Galbraith et al. 1999) =					0.57±0.01	66	0.30±0.01
UNL2830	MOV-SL-50	1.7	12.0	2.00	0.05	2.43	0.12	7.07	0.30	0.18	2.55±0.10	2.13±0.10	54	0.83±0.05
UNL2832	MOV-TK-2	1.5	7.1	1.55	0.04	1.78	0.10	5.77	0.26	0.18	2.12±0.08	1.63±0.10	59	0.77±0.05
							Minimum Age Model (Galbraith et al. 1999) =					1.03±0.10	59	0.49±0.05
UNL2833	MOV-OSW-59	2.1	27.9	1.76	0.05	2.36	0.13	7.57	0.29	0.17	2.05±0.11	4.45±0.09	57	2.17±0.12
							Minimum Age Model (Galbraith et al. 1999) =					3.68±0.04	57	1.80±0.10
UNL2834	MOV-SL-49	1.8	11.7	2.07	0.05	1.92	0.11	5.92	0.25	0.17	2.43±0.09	1.66±0.11	58	0.68±0.05
							Minimum Age Model (Galbraith et al. 1999) =					0.86±0.09	58	0.35±0.04

* In-situ Moisture Content
D_e calculated using the Central Age Model (Galbraith et al. 1999) unless otherwise indicated.
Error on D_e is 1 standard error
Error on age includes random and systematic errors calculated in quadrature

4.1.1 Salix Quandrangle

4.1.1.1 Location and Specifics

The Salix gooseneck in the Salix, IA Quadrangle (SLX) is located at the southeastern corner of the quadrangle approximately 3 kilometers south of the city of Salix. The Salix gooseneck allo-unit covers an area 7.2 to 7.6 km long north to south, of which 3.2 km of the east arm of the Salix gooseneck continues south out of the Salix Quad into the Albaton Quadrangle, IA-NE and is 4 km wide west to east (Figure 4.1). The channel length for the Salix gooseneck is approximately 14 kilometers. The channel sinuosity of the Salix gooseneck measured from the beginning of the west arm to the end of the east arm is 5.0. The point bar inside the Salix loop (Bar 1), from the bottom of the Salix Quadrangle to the head of the bar, is approximately 5 km long. Bar 2, encroaching into bar 1 from the west is 0.6 kilometers in length.

4.1.1.2 OSL Data

Two OSL samples were collected in the Salix Quandrangle (Figure 4.1). An OSL sample was taken from borehole MOV-SLX-50 (incorrectly labeled MOU-LSY-50 during processing - Table 4.1) in a ghosting point bar that was found on the north end of the Salix Quad, approximately 11 km north of the Salix gooseneck. The point bar was located 4 meters under the surface covered splay material. The sample was collected and processed by the 2009 work team and was dated at 12.2 +/- 0.7 ka. For the purposes of this Master's thesis, it was decided that we needed to come back to the Salix Quad and take an OSL sample for dating inside the gooseneck loop. The hole, MOV-SLX-57, was drilled and a 20 centimeter was sample collected at a depth of 1 meter on the last ridge of the gooseneck loop before the point bar sloped down into the channel scour to the west. The SLX-50 sample was dated at 0.43 +- 0.03 ka, so the Salix gooseneck is less than 500 years old

4.1.1.3 Scroll Pattern and Development

The flow of the channel starts at the west arm of the gooseneck channel and out of the east arm. There are 2 accreting sandbars involved in the evolution of the Salix gooseneck loop;

the point bar inside the channel loop, Bar 1, and the bar on the west side of the Salix gooseneck cutting into bar 1 forming the front “neck” of the gooseneck, Bar 2. Bar 2 is continually migrating east as the west arm of the channel is eroding into Bar 1, chewing up relatively recent, easily erodible sand deposits. Bar 2 turns gradually to the northeast (Figure 4.1). The initial length of the west channel arm of the gooseneck is wide where several braided channels merge together as it enters the first part of the gooseneck. The topographic relief in between the channel and bounding point bars is also visible in the field because the channel hasn’t been completely filled in with sediment. Following the meander scroll pattern of Bar 1 inside the Salix gooseneck, the east arm of the channel migrates to the east, cutting into a splay covered “ghost” channel and point bar. A “ghost” channel is a buried channel ghosting through its cover and is barely discernible.

The head of the loop rotates counterclockwise as it grows up-dip eroding into the splay material and depositing point bar sands in a northern direction. About 2 to 2.4 kilometers into the Salix gooseneck, the channel migration changes direction and expands laterally to the west while still expanding to the north. The westward migration produces the “bill” of the loop. Simultaneously, the scroll patterns show that the channel also expands to the northeast forming the back of the head before the channel finally arcs back to the south.

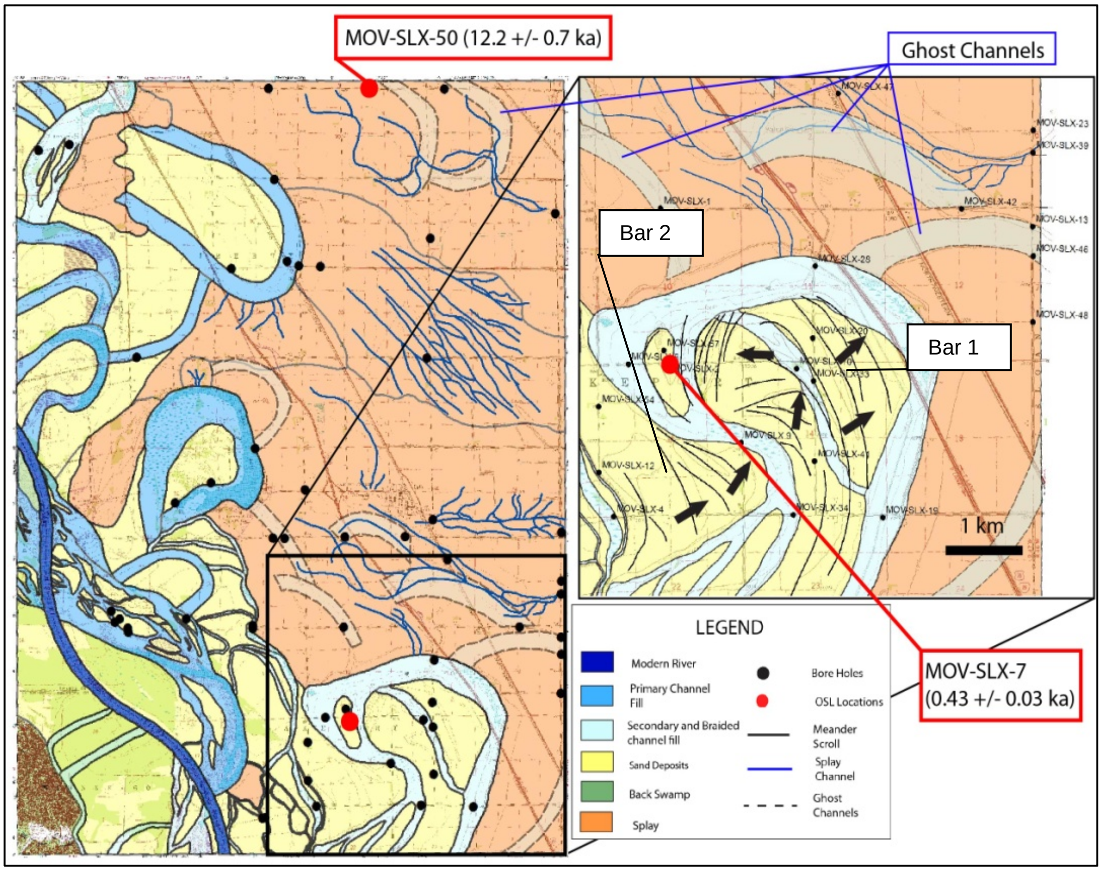


Figure 4.1: Salix Gooseneck. Arrows indicate the direction of meander migration

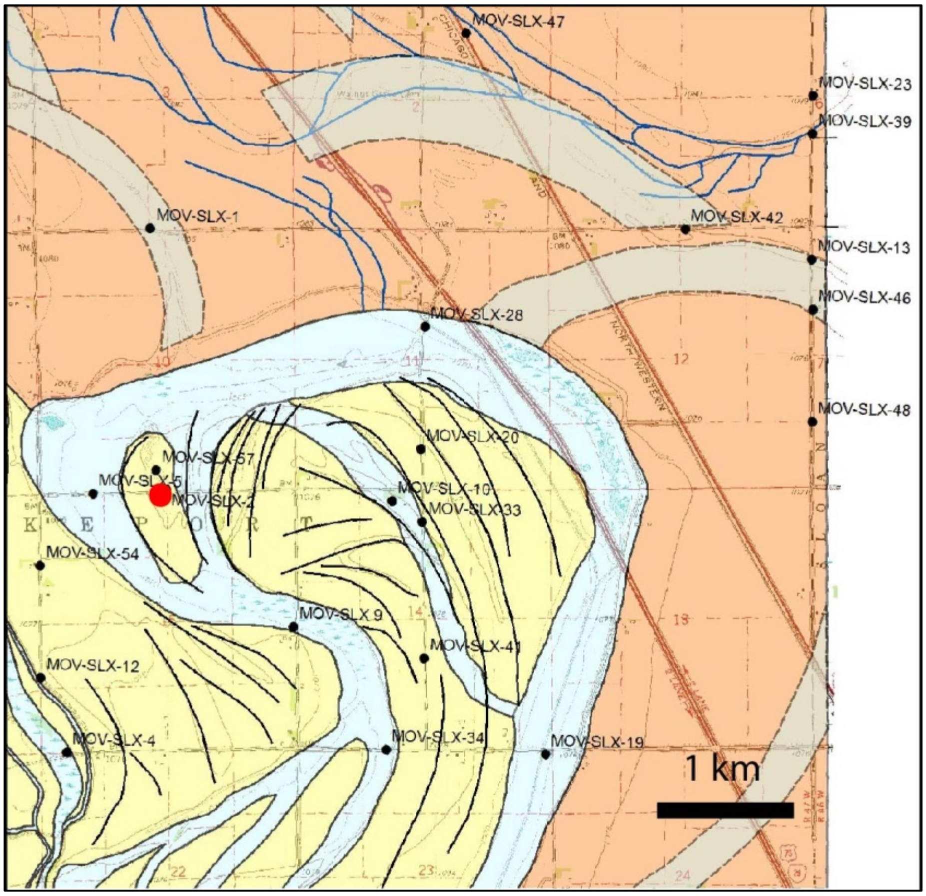


Figure 4.2: Salix Gooseneck drill-hole locations.

4.1.1.4 Borehole Data

There are 5 logged boreholes within the splay deposits north and east of the Salix loop (Figure 4.2). Borehole MOV-SLX-1, north of the gooseneck loop consists of fine grained splay material, mostly loams and Silty Loams in the first 2 meters drilled. There are one or two thin layers (< 20 cm) of Silty Clay and Clay. The bottom 2.5 meters fines into passive channel fill of Clays and Silty Clay.

To the immediate east and northeast of the Salix gooseneck, a channel and accompanying point bar are seen ghosting through the overlying splay material. The ghost channel is visible on aerial photography, and distinguishable in topographic maps via a levy that boarders the north edge of the channel going off the Salix Topographic Map to the east. Borehole's MOV-SLX-13, 42, 46 and 48 confirm the presence of the ghost channel. Borehole

42 was drilled into splay just north of the ghosting channel. The first meter of the drill hole is dominantly loamy sand. Below that the material fines toward silty clay before jumping back up to fine sand in the 5th meter. Just to the south and east of SLX-42 is SLX-13. SLX-13 is in a topographically low area and identifiable as the location of the ghost channel. The first 3.5 meters of the hole is silty clay mudflat followed by .8 meters of alternating lenses of sandy loam to silty clay splay material before turning back to clay with some of the clay just bordering on the silty side for the remainder of the borehole. The dominance of the silty clay and clay shows that this would be an area for water to pool and allow the finer sediments to settle out of the water. In the next drill hole further south, SLX-46, is mostly absent of clay and silty clay. It is dominantly splay material consisting of a meter of silty loam overlaying a little over a meter of sandy loam. Below that, the next 1.7 meters is a mixture of silty loam and loam before becoming dominant silty loam for the rest of the hole. In the final hole of the splay area, SLX-48, a ghost point bar is encountered. The first 4.4 meters of the hole is all silty loam. For the next 0.5 meters, the alluvium coarsens and fine sand is reached at 5.3 meters deep and indicates the top of the buried point bar inside the "ghost" channel mapped and confirmed with holes MOV-SLX-13 and 46.

Drill Holes MOV-SLX-5, 9, 19, 28 and 34 were dug in into the channel fills of the Salix gooseneck. SLX-19 and 28 are dominantly clay and silty clay. Borehole SLX-34 is dominantly silty loam all the way to the bottom of the hole. The first 3.8 meters of SLX-5 is all silty clay then coarsens to fine sand indicating that the drillers penetrated the channel fill and reached the end of the loop's point bar. There are mid channel bars within the western arm of the gooseneck loop, indicating that the channel was braiding until just a little upstream of the first bend of the gooseneck prior to cutoff. MOV-SLX-9 was drilled just downstream of the apex of the first sharp channel bend within the west channel arm along the inner bank. The first two meters of the hole is silty clay channel fill, but in the final two meters, the sediment coarsens abruptly into medium sand indicating point where strong enough flow existed along the entire width of the channel to keep pushing bed-load sediment downstream.

Holes, MOV-SLX-2, 20, 33, 41 and 57, were drilled into Bar 1 of Salix gooseneck and are all dominantly sand. Additionally, MOV-SLX-54, was drilled just to the west of the “beak” of the Salix loop and is 1.3 meters of sediment ranging from silty clay to loam before it coarsens into the fine sand of Bar 2 at a depth of 3.9 meters. MOV-SLX-10, also drilled into the Salix gooseneck, indicated the presence of a chute channel that cut across a section of the gooseneck loop for a time. The point bar sands of the other holes inside the gooseneck were reached within a meter from the surface, but the point bar material of SLX-10 was not reached until 4 meters down. The top 4 meters was composed of the active channel fill of a chute channel varying from silty clay to fine sand, never staying at any grain size for more than 30 centimeters.

4.1.2 Sloan Quadrangle

4.1.2.1 Location and Specifics

The next gooseneck preserved within the valley floor is located in the southern part of the Sloan Quadrangle, IA (SL). It is located 7.6 kilometers south of Sloan, IA and 3.2 kilometers west of Whiting, IA. The Sloan loop is not contained completely within the Sloan Quadrangle. The arms of the Sloan loop extend south out of the Sloan Quadrangle, turning west where they terminate shortly after passing into the Albaton, IA-NE and Macy, IA-NE Quadrangles. The Sloan gooseneck allo-unit is 5.6 km long, north to south, and 4 km wide, east to west (Figure 4.3). The length of the channel is approximately 18.5 km long from end with a sinuosity ratio of approximately 7.7. The length of the point bar inside the Sloan Loop, designated Bar 1, starting at the south boarder of the Sloan Quad is 3 km long to either its northern most bar termination or its western most bar termination. The entire bar length starting at its termination in the Macy Quadrangle, IA-NE is 8 km. The western most sand bar, Bar 2, is one 2.4 km in length and Bar 3 immediately to the east of the Sloan gooseneck is a little less than 1 kilometer wide.

4.1.2.2 OSL Data

Five OSL samples were gathered within the area surrounding the Sloan Gooseneck. Four of the OSL locations are within the Sloan Quadrangle; the fifth is just to the south within the Onawa SW Quadrangle, IA. Three samples were collected by the 2009 field group, and the other two by the 2010 field group. Sample MOV-SL-3 was obtained east of the Sloan gooseneck within the most recognizable point bar furthest east and is dated at 6.59 +/- 0.42 ka (Figure 4.4).

The two other samples collected, MOV-SL-47 and MOVOSW-58, prompted a return to the Sloan Quad for additional sample gathering by the 2010 field group. Sample MOV-SL-47 was taken inside the Sloan Gooseneck, in Bar 1, and was dated at 6.59 +/- 0.42 ka. Sample MOVOSW-58 was taken from a point bar approximately 3 kilometers southeast of MOV-SL-3 and returned a date of 0.68 +/- 0.06 ka.

As discussed earlier in this work, mapping the allostratigraphy of the Missouri River channel belt allows us to determine the relative ages of different channel and bar units, but not specific ages; a younger channel will cut off or erode into an older channel/bar allo-unit. Based on the relative aging that allostratigraphy shows us, the Sloan gooseneck cannot be older than the sample taken from borehole MOV-OSW58. Each progressive loop cutoff getting closer to the modern Missouri would get increasingly younger.

It is believed that the OSL data for holes MOV-SL-47 and MOV-OSW58 were accidently swapped by the 2009 field group during soil processing in the labs at the University of Nebraska at Lincoln. Since there was no discernible proof there was a mix up between the two samples at the lab, the OSL data for both holes is considered invalid. The information is mentioned here for the sake of completeness.

During the 2010 field work, in light of the mix up of OSL dates for holes MOV-SL-47 and MOV-OSW58, we decided to go back to the Sloan Quad for additional OSL dating. Instead of trying to date inside the Sloan gooseneck again, we chose to date the point bar (Bar 2) just upstream of the gooseneck, migrating into the loop forming the “neck” and “chin” of the gooseneck. We took the samples to help confirm or deny the data of MOV-SL-47 and also to try and determine a rate of point bar accretion. OSL sample MOV-SL-50 was collected near the termination of the point bar at the east end of Bar 2 near the “neck” of the gooseneck channel. Sample MOV-SL-49 was collected about 1.4 km further west where the meander scrolls turns from the south to the east into the increasingly sinuous meander bend. MOV-OSL-49 was dated at 0.68 +/- 0.05 ka and the bar termination sample, MOV-SL-50, returned a date of 0.83+/- 0.05 ka. These two additional samples proved our suspicion that the dates for MOV-SL-47 and MOV-OSW58 were not correct. Unexpectedly, the sample of the loops termination is older than the OSL sample near the base of the point bar. A closer look at the scroll patterns for the Sloan gooseneck is required.

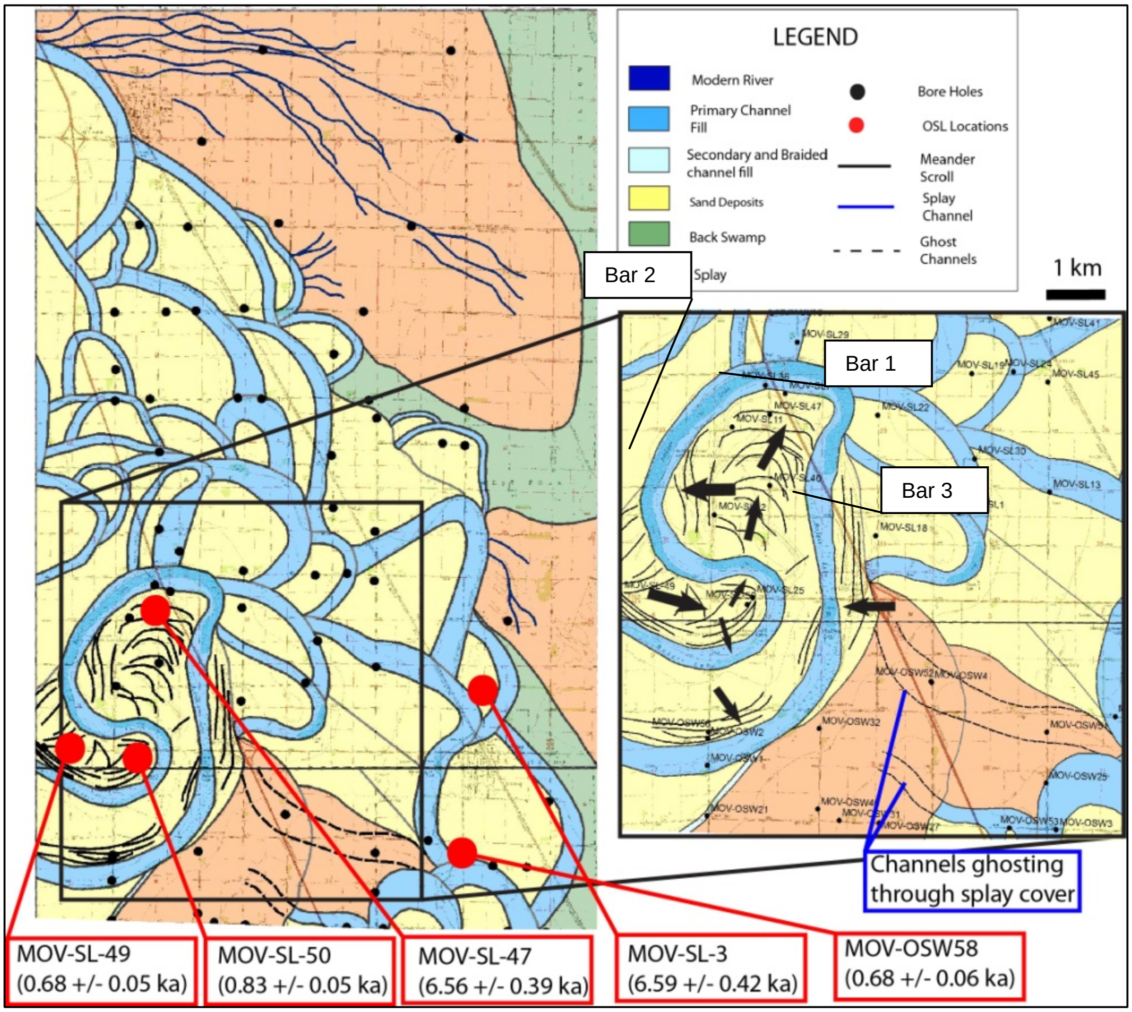


Figure 4.3: Sloan Gooseneck. Arrows indicate the direction of meander migration.

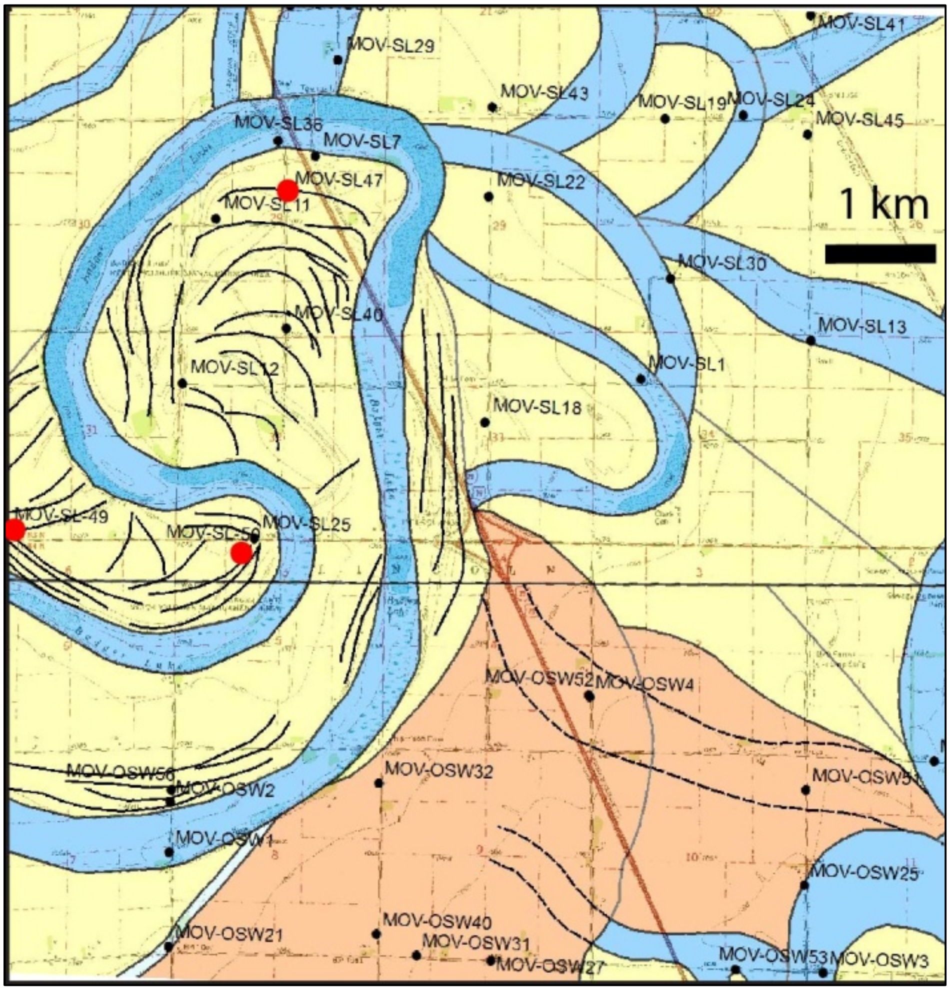


Figure 4.4: Sloan Gooseneck drill-hole locations.

4.1.2.3 Scroll Pattern and Development

Bar 2 migrates into the Sloan gooseneck forming the lower head and neck of the loop. The meander scroll pattern indicates that the channel migrated in a southeasterly direction then turned east cutting into the Sloan gooseneck. Near the end of the point bar the channel started cutting/depositing sediment to the north and more importantly, to the south. The entire upstream point bar starts migrating to the south with the highest amount of deposition at the point bar termination and the least at the upstream end.

When the location for OSL sample MOV-SL-49 was chosen, it was thought that the location was at the base of the meander loop just as the meander scroll patterns turn east.

When Dr. Holbrook and I arrived at the physical location we observed the direction change of the point bar because of a scarp along the line of directional change where the river underwent incision into the valley floor or owing to how far the away the Sloan channel loop had been cut off, never completely filled in with sediment. We believed we'd chosen an appropriate location where the scrolls and channel turned east.

The OSL data came back and revealed the sample MOV-SL-49 was actually younger than MOV-SL-50 when we expected it to be older. This prompted a more in-depth look at the scroll patterns. Recent aerial photos (<5 years) revealed no insights, possibly due to vegetation cover. A look at a 1930s aerial survey of the area showed the scroll patterns not observed in the more recent photography. MOV-SL-49 was taken at the upstream location where the point bar starts migrating completely south (Figure 4.5). This is the thinnest location of deposition, which grows wider as it gets closer to what is the apex of the first end in the Sloan gooseneck and post dates the part of the bar form dated in sample MOV-SL-50. The point bar takes approximately 150 years to finish migrating east then shift south. Owing to how narrow the directional change of accretion is at MOV-SL-49, it is unclear if this sample represents the beginning of the direction change, the end or somewhere in the middle.

Bar 2, in the neck portion of the loop, scroll pattern indicates an eastward migration along the east edge of the neck. In the head of the loop, the patterns show that the bar turned north. Patterns prior to the turn north were eroded by Bar 1 as it was forming the front of the "neck" of the gooseneck. About half way up the head of the inner bar, approximately 1.6 km north of the Sloan Quad boarder, the channel pattern adds a western trajectory forming the "bill" of the head.

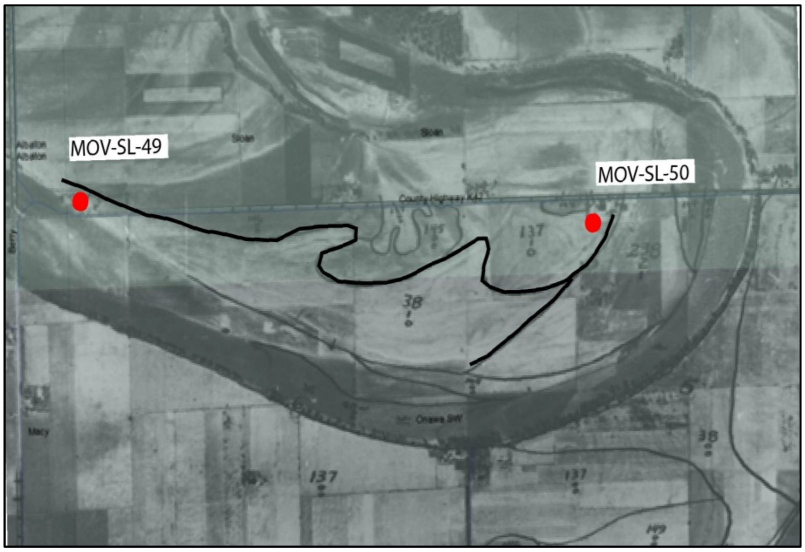
This gooseneck has a 3rd sand bar, Bar 3, which is present immediately east of the channel forming the gooseneck. This third point bar indicates that the east arm of the channel as it is exiting the loop, stopping migrating laterally to the east, and started shifting west. Given enough time, it would have resulted in a neck cutoff.

4.1.2.4 Borehole Data

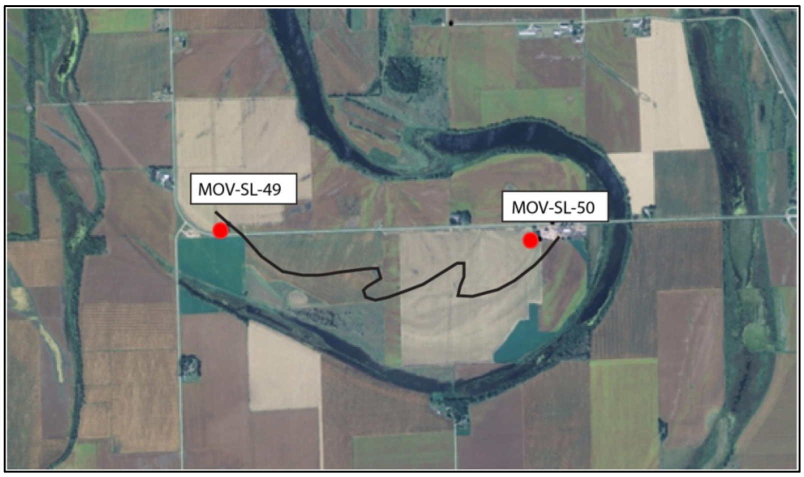
All holes drilled into Bar 1 and 2 within the Sloan gooseneck, MOV-SL-7, 11, 12, 25, 47, 49 and 50 & MOV-OSW56, exhibited the fine sand of point bar material within the first meter drilled (Figure 4.4). Borehole MOV-SL-40, also drilled within Bar 1, was composed of coarse sand. To the north of the Sloan gooseneck, holes MOV-SL-10 & 29 were channel fill deposits confirming a hairpin channel that goes north and turns sharply south back into the Sloan gooseneck. Bore holes MOV-SL-43, 22 and 18 were drilled into bars just east northeast to east (respectively) of Bar 3. Hole 22 was fine sand and 18 was coarse sand.

To the southeast of the Sloan gooseneck, within the Onawa SW Quadrangle, the allostratigraphy of the area gets complicated. A number of holes were drilled, MOV-OSW6, 21, 27, 31, & 32, where point bar material was reached at various depths of 3 to 4.5 meters topped by splay material, but no discernible allo-units were easily identifiable via physical observation or changes in topography. Some ghost channels could be recognized in the aerial images. For example, MOV-SL-4 and 51 are within a buried channel terminating into Bar 3 of the Sloan Gooseneck.

The ghost channels were originally thought to be related to the same submerged channel belt found in the Salix Quandrangle. However, bore holes drilled further east in older point bars, (i.e. MOV-OSW41 &39) were at the surface and clearly not associated with the much older buried belt identified within the Salix Quad. A closer look at the topographic maps revealed that the central portion of the Sloan Quad exhibited an overall 10 foot change in relief sloping to the east. About a quarter of the channel belt in the Sloan Quad is covered by thick local splay deposits. The local splay deposit has been eroded on the north end to the Sloan gooseneck. A braided Missouri River has chewed into the splay on the west and the Onawa Southwest gooseneck cut into it from the south.



(a)



(b)

Figure 4.5: Sloan loop past and present with OSL locations (a) 1930s aerial survey, (b) recent survey (< 10 yrs). Notice that the scroll patterns are easily depicted in the 1930s photos.

4.1.3 Onawa SW Quadrangle

4.1.3.1 Location and Specifics

The next gooseneck is located on the south end of the Onawa Southwest Quadrangle, IA (OSW). The Onawa SW gooseneck location is 3 kilometers west of town of Onawa, IA. This loop has not filled in fully with sediment and is currently an oxbow lake called Blue Lake; the north tip of which serves as the site of the Lewis and Clark State Park. Almost the entire loop is contained in the Onawa SW Quadrangle (Figure 4.6); approximately 0.8 kilometers of the east arm extends south into the Tekamah NW Quadrangle, IA-NE before it terminates against a younger loop. The Onawa SW gooseneck allo-unit is a little over 5.5 km long, north to south, and 4.8 km wide east to west. The channel length of the gooseneck loop is approximately 15.3 kilometers long from end to end with a sinuosity ratio of 4.3. The point bar inside the Onawa SW gooseneck loop, Bar 1, is roughly 4 km long. Bar 2, to the west of the loop is a 1.8-1.9 km wide and Bar 3 to the east is approximately less than a kilometer wide.

4.1.3.2 OSL Data

Only one OSL sample was collected by the 2009 field group. This sample is in the center of the loop, approximately 1.5 km north of a younger channel cutting into the Onawa SW gooseneck. The sample for this hole, MOV-OSW12, is dated at 0.59 +/- 0.05 ka (Figure 4.6).

4.1.3.3 Scroll Pattern and Development

The scroll patterns of the Onawa SW gooseneck are not as complex as the previous loops and never reached such extreme sinuosity (Figure 4.6). The meander scroll patterns of this loop are traceable for 3 different bars: Bar 1 inside the loop, Bar 2 to the west of the loop, and Bar 3 to the east. While the Onawa SW loop doesn't mirror the recognizable gooseneck form of previous loops, it still maintains the characteristic up-dip migration pattern shared by the other loops. The directional flow of the channel is from the west arm of the Onawa SW gooseneck through the crest and to the east arm.

The scroll pattern for Bar 2 indicates the west leg of the channel migrating to the east. For bar 1, the northern 2 km of the point bar reveals that the river was migrating north, while the southern two-thirds of the OSW gooseneck Bar 1 is migrating to the east. Bar 3 contains the remnants of channels of the Onawa SW channel which was migrating laterally to the east, but then eventually shifted direction back to the west. When the eastern arm of the Onawa SW loop moved back to the west via either migrations or chute cutoff, mid-channel bars were deposited eventually cementing to the east side of the river channel.

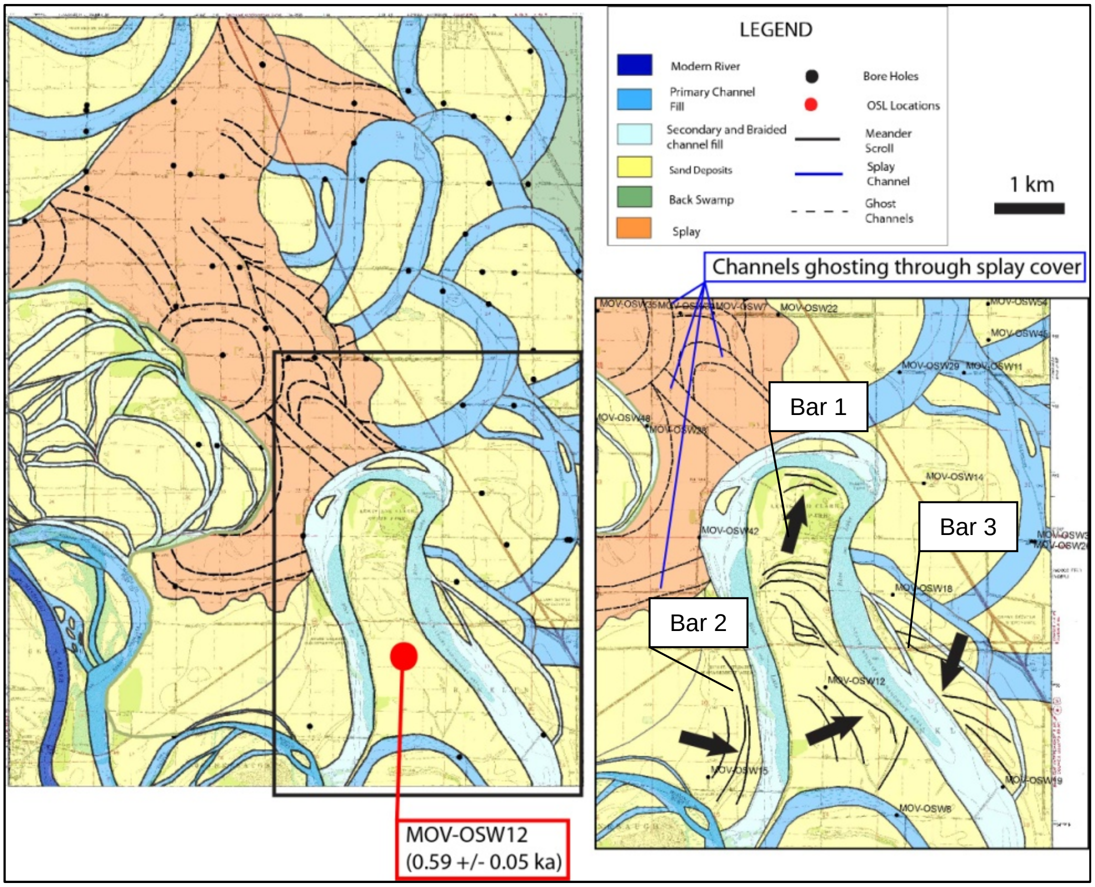


Figure 4.6: Onawa SW Gooseneck. Arrows indicate the direction of meander migration.

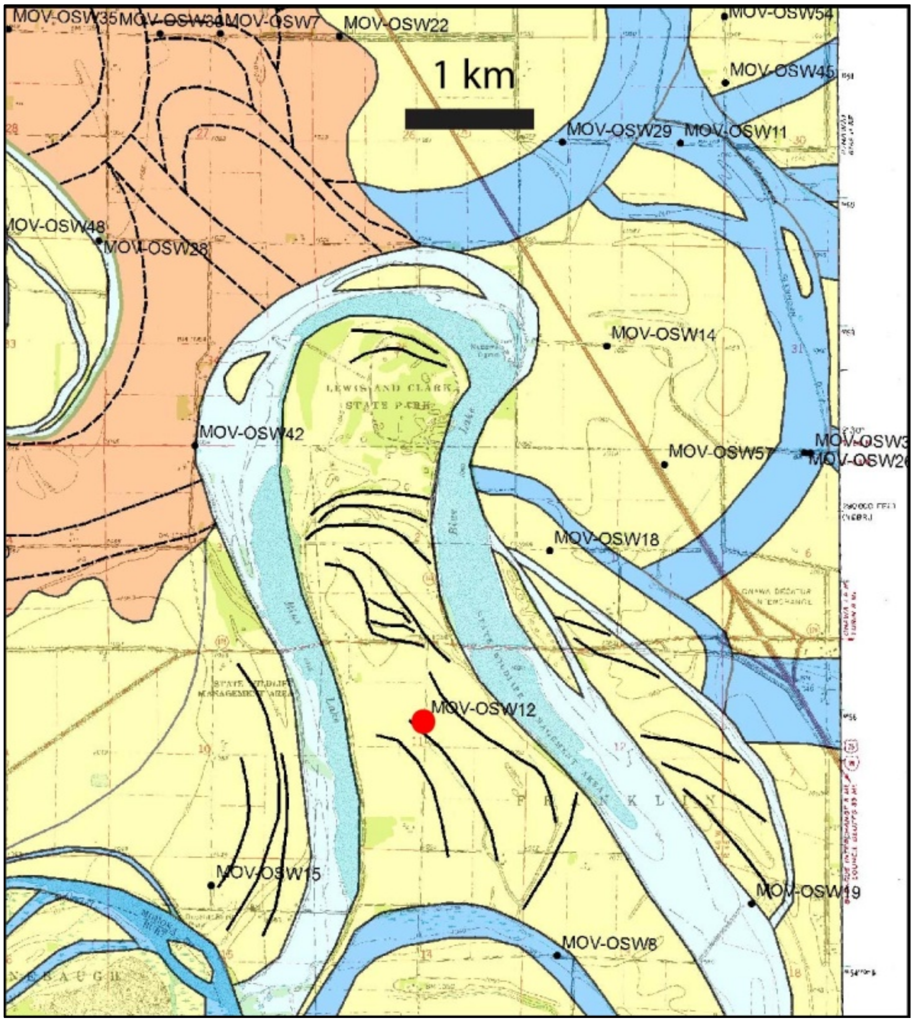


Figure 4.7: Onawa SW Gooseneck drill-hole locations.

4.1.3.4 Borehole Data

MOV-OSW15 was drilled into Bar 2, confirming the presence of the western point bar. Likewise, MOV-OSW18 and 19 confirmed Bar 3 (Figure 4.7). Further north, in an older loop directly east of the head of the Onawa SW gooseneck, holes MOV-OSW14 and 57, are dominated by sandy deposits.

At the far north tip of the OSW gooseneck, MOV-OSW-29 shows a wide and thick clay channel fill over 7 meters deep. Northwest of the OSW gooseneck loop is the southern edge of the splay material discussed previously in the Sloan section. Two ghosting channels were visually identified under the splay material using recent aerial photography. Both channels dead-end into the head of the Onawa SW gooseneck. Log data of holes, MOV-OSW22 and 35, indicate the continued presence of 3 meters of splay deposits covering the area.

4.1.4 Little Sioux Quandrangle

4.1.4.1 Location and Specifics

Continuing south down the field area, the next gooseneck loop isn't encountered until reaching the Little Sioux Quandrangle, IA-NE (LS), located at the north end of the Quadrangle approximately 4.8 km north of the town of Little Sioux, IA (Figure 4.8). The Little Sioux gooseneck is 4 km long north to south and 4.8 km wide east to west. The loop resembles a classic meander loop that was very close to becoming a horseshoe shaped oxbow lake, but a neck cutoff never occurred. While it doesn't exhibit the now familiar gooseneck shape, the Little Sioux gooseneck also turns up-dip against the expected normal water flow. The channel length of the Little Sioux gooseneck is 11.3 kilometers long with a sinuosity ratio of approximately 4.7.

4.1.4.2 OSL Data

Two OSL samples were collected inside the Little Sioux gooseneck for the purposes of determining an age and a rate of accretion. The 2010 field group collected OSL sample MOV-LS-30 near the "base" or south end of the meander loop. Sample MOV-LS-34 was taken approximately 2.4 km north near the termination of the bar. Sample LS-30, at the base, is dated at 1.44 +/- 0.08 ka and sample LS-34, at the termination, is dated at 1.89 +/- 0.11 ka (Figure 4.8). The termination of the loop is older than the sample taken at the base of the loop. A similar pattern of dating occurred in the Sloan gooseneck, which was mentioned earlier in this study. Like Sloan, a closer look at the scroll patterns of the Little Sioux gooseneck sandbar is required.

4.1.4.3 Scroll Pattern and Development

The meander scrolls preserved within the point bar inside the Little Sioux gooseneck, Bar1, show a northward migration pattern that eventually turns northeast near the bar termination. At the base, in the general location that borehole MOV-LS-30 was drilled, the scroll pattern shows that the river channel started migrating to the southeast. The younger date of LS-30 at 1.44 +/- 0.08 ka implies this southeast migration started after the sand at MOV-LS-34 was deposited. If the sample collect at the base was taken further to the west near boreholes MOV-LS-28 or 29, then the sample would have provided an adequate time frame for the formation of the entire bar. Bar 2, upstream of Bar 1, migrates eastward almost resulting in a neck cutoff, which never occurs.

4.1.4.4 Borehole Data

Holes MOV-LS-28, 29, 30, 31, 32, 34, and 51 inside the Little Sioux gooseneck are dominated by fine sand, and holes MOV-LS-17 and 44 are channel fills on the west and east arms of the channel around the point bar (Figure 4.9). East of the Little Sioux gooseneck are the remnants of small older channel/bar allo-units separating the gooseneck loop and older back swamp strata. Sandy bar material accreted by its down development is on the west side of the Little Sioux loop.

The northern tip of the Little Sioux gooseneck extends into the Blencoe Quadrangle, IA. The map for Blencoe was still undergoing editing at the time of this study; however, the necessary boreholes were analyzed and the appropriate allo-units mapped into the Blencoe Quadrangle to complete the borehole discussion. Borehole MOV-BNC-9 was drilled immediately north of the Little Sioux gooseneck and hit sand bar material at 3 meters depth. Approximately a half a kilometer north, MOV-BNC-31 was drilled into channel fills composed of dominantly clay and silty clay. The east arm of this older channel curves to the south where it is cut off by the Little Sioux Gooseneck.

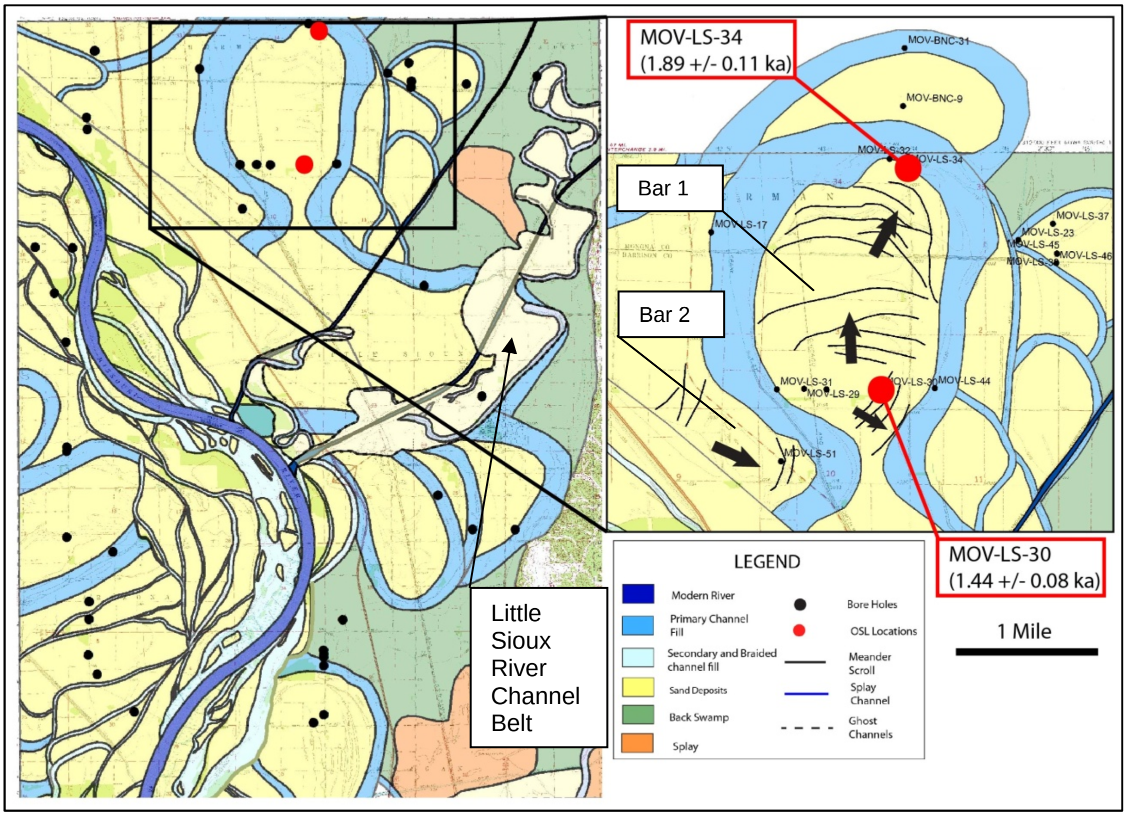


Figure 4.8: Little Sioux Gooseneck. Arrows indicate the direction of meander migration.

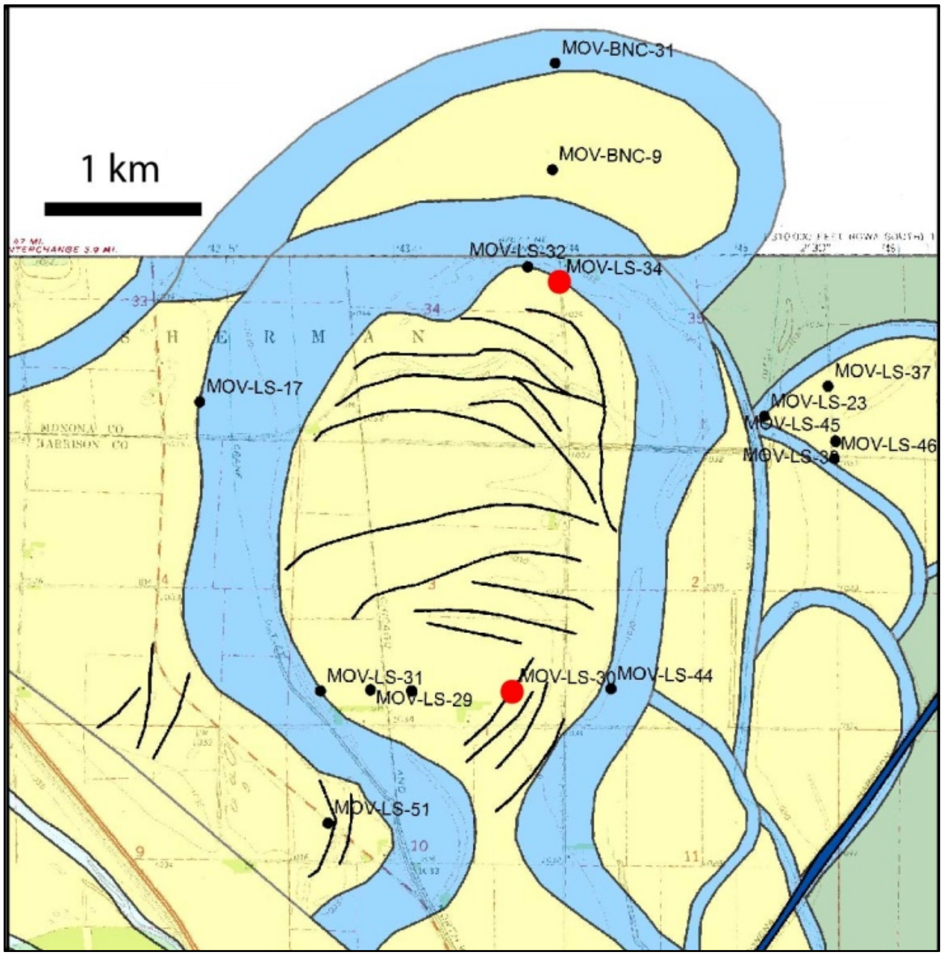


Figure 4.9: Little Sioux Gooseneck drill-hole locations.

4.1.5 Mondamin Quadrangle

4.1.5.1 Location and Facts

The Mondamin Quadrangle, IA (MD), immediately south of the Little Sioux, represents the end of the mapping and field research area. This quadrangle was mapped by UT Arlington graduate students Michele Kashouh and Daniel Carlin. The Mondamin Quadrangle contains one gooseneck, which is positioned in roughly the center of the map 2.4 kilometers southwest of the town of Mondamin, IA and roughly 2.4 km east of the modern Missouri River (Figure 4.10). The eastern half of the loop is easily recognizable on aerial and topographic maps, whereas the western half is not clearly distinguishable. The channel scar in the east loop clearly hasn't filled in with sediment and exhibits upwards of 1.8 to 2.4 meters of relief from channel bottom to the top of the outer cutbank. The west loop is practically flat by comparison revealing a change in relief of 0.3 to 0.5 meters. The direction of water flow for the Mondamin gooseneck is from the west arm of the meander out the east arm. The Mondamin Loop, including point bars, is about 5.1 km long from Northwest to Southeast and 3.2 km wide from Northeast to Southwest. The length of the channel loop is approximately 13.7 kilometers long with a sinuosity ratio of about 11.3

4.1.5.2 OSL Data

No OSL data was collected from the Mondamin Quadrangle. Owing to the substantial resources required for processing OSL samples and the limited funding available, it was decided during our 2010 field work that samples collected within the other quadrangles would prove more effective. Specifically relating to the meander loops focused on in this research, we not only wanted to determine the ages of the goosenecks, but also to determine a rate of deposition of the gooseneck bars. The pattern of the meander scrolls in the Mondamin gooseneck did not appear conducive to our modified approach of acquiring dates and rates.

4.1.5.3 Scroll Pattern and Development

The Mondamin loop has 3 point bars. Bar 2 to the west is the bar just upstream of the channel moving into the gooseneck and also forms the “neck” and “chin.” Bar 1 comprises the deposition of the bar inside the Mondamin gooseneck, and Bar 3 on the north side of the loop, cuts into the gooseneck forming a double lobed gooseneck (Figure 4.10).

Most of the meander scrolls associated with Bar 2 have been eroded by a younger channel. The younger channel cut off the Mondamin gooseneck sometime in the past and then started destroying Bar 1. The scroll pattern remaining shows that the river cut from west to east into the bar inside the loop forming the “neck” and “chin” of the gooseneck loop.

Much of the scrolls within Bar 1 have been removed by Bar 2, but analysis of Bar 1 in conjunction with Bar 3 help determine the migration pattern of the Mondamin gooseneck channel. Bar 1 is split into two lobes for the sake of clarity; Lobe 1 to the west and Lobe 2 to the east. The scrolls of Lobe 2 within the Mondamin gooseneck indicate lateral migration to the east cutting into the remnants of an older meander loop partially covered in splay. The scrolls within Lobe 1 of the meander only show up in the "bill" of the gooseneck. Any scroll patterns building up to the development of the two lobes is missing owing to growth of Bar 2. The west arm channel was close to undergoing a neck cutoff with the east arm prior to abandonment. Starting at the southeast end of Lobe 1, the scroll patterns exhibit a north trending migration. One and a half kilometers into Lobe 1, about half its length, the scroll pattern shifts exclusively to a northwest direction.

Bar 3, on the north side of the Mondamin gooseneck, preserves scroll patterns and channel fills that indicate the Mondamin loop had once migrated further north. When the formation of Lobe 1 initiated, the Mondamin gooseneck stopped cutting to the north and reversed direction southwest into its own bar deposits. The shape of the preserved channel fills support the change in channel migration by sharing the same rough shape as the Mondamin gooseneck. Additionally, the scroll patterns in Bar 3 show bar accretion to the southwest.

4.1.5.4 Borehole Data

Two holes, MOV-MD- 39 and 40 were drilled into Bar 3 of the Mondamin gooseneck (Figure 4.11). Borehole MD-40 is composed channel fill for the first 3 meters coarsening downwards from Clay to Sandy Loam reaching at 3 meters. Hole MD-39 is topped with 2.3 meters of channel fill before reaching the sand of the channel bottom/underlying bar.

Lobe 1 of the Mondamin gooseneck is cutting into the remnants of an older meander loop. Holes MOV-MD-4 and 5 were drilled into the cut bank on the inside and outside of the older loop to constrain the channel width. Borehole 4, inside the loop, shows the area has 2.2 meters of splay material covering the fine sand point bar. Outside the loop, borehole 5 reaches point bar material at 3 meters.

North of the Mondamin Gooseneck in Bar 3, from the west side of the loop to the east side, the valley alluvium consists of point bar material inside a channel fill with splay to the east of the channel fill wrapping around Bar 3 where boreholes MOV-MD-47 and 45 were drilled. Finally to the east, drill hole MOD-MV-11 consisted of 3 meters of splay material overlaying sandy bar deposits. There is no data for the northwest termination of the lobe since a younger Missouri River has since already migrated into Lobe 1. MOV-MD-11, to the west is bar material topped with some splay and immediately west of the hole is a sharp decline of elevation of 3 meters indicating a terrace cut by a younger braided system.

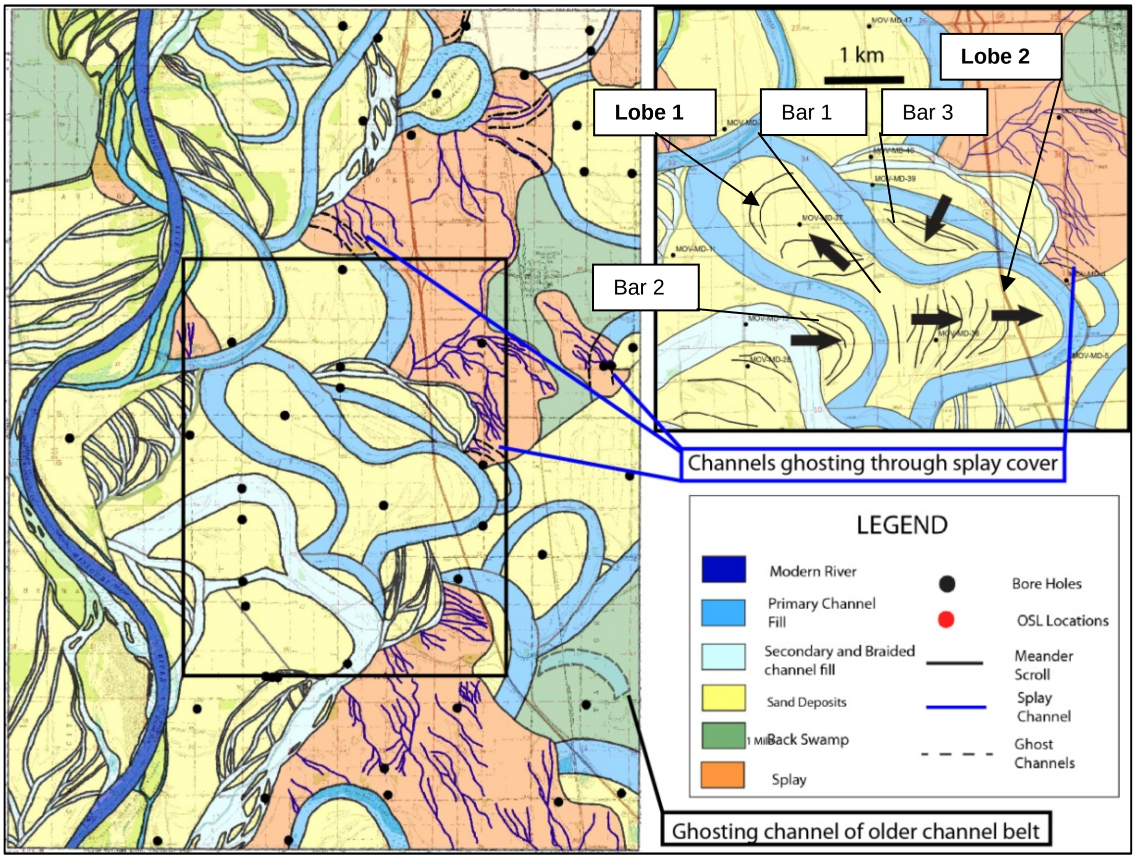


Figure 4.10: Mondamin Gooseneck Loop. Arrows indicate the direction of meander.

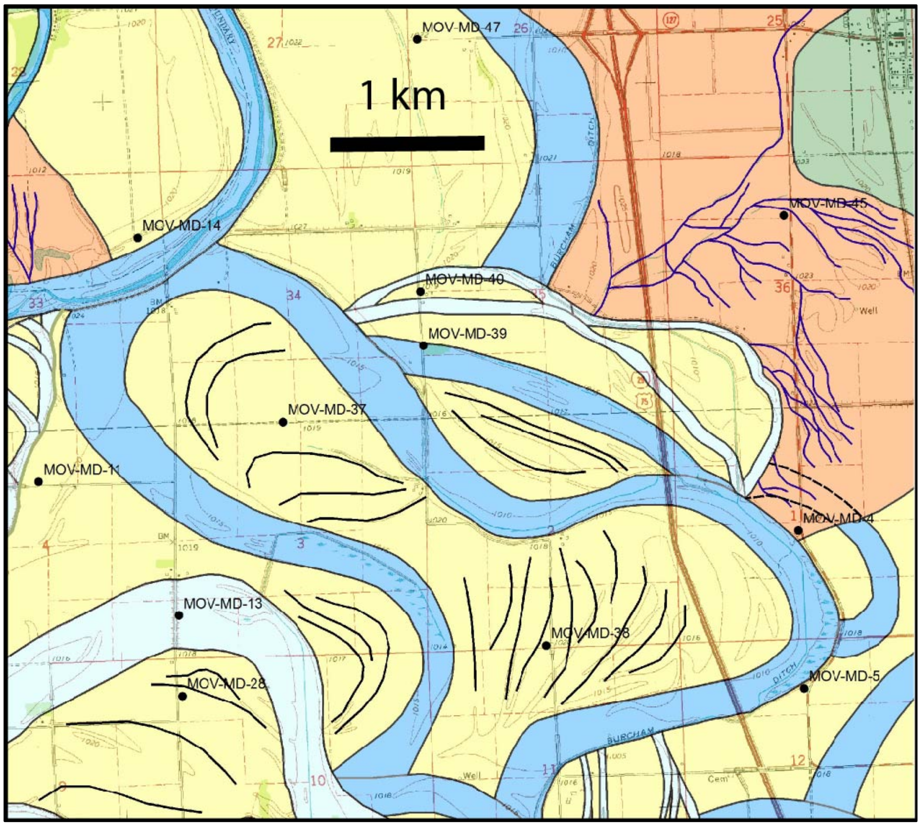


Figure 4.11: Mondamin Gooseneck drill-hole locations.

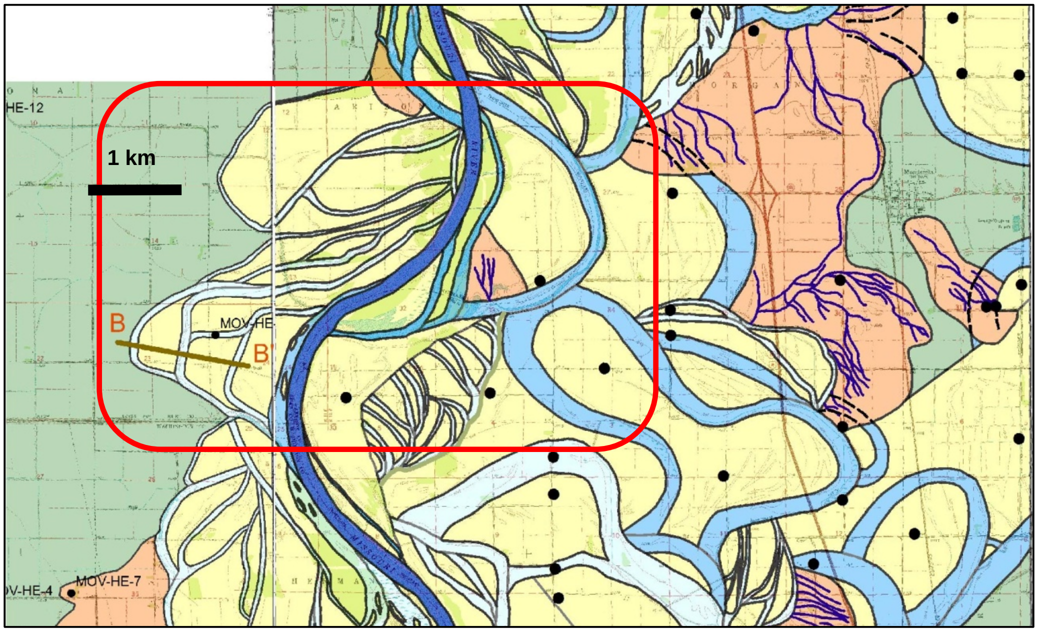
4.1.6 Herman Quadrangle

4.1.6.1 Location and Specifics

The Herman Quadrangle, IA-NE is immediately west of the Mondamin Quadrangle and does not contain a gooseneck. However, Herman contains a section of the west boundary of the Modern Missouri River channel belt. Recent aerial photography doesn't reveal the age of the western edge of the Missouri channel belt; however the 1930s survey prior to channelization does (Figure 4.12a, b). As early as 1930, the Missouri River was migrating laterally toward the western Missouri River Valley and at the western edge of its belt before it was cutoff by human modifications.

4.1.6.2 Borehole Data

Four holes were drilled west of the channel belt trying to find any buried features. Boreholes MOV-HE-7 and 8 consist of 2.5 to 3 meters of splay material overlaying 4 to 5 meters of back swamp material (clay). Boreholes MOV-HE-1 and 5 were drilled to depths of 6 and 8 meters (respectively) and are composed entirely of back swamp material.



(a)

(b)

Figure 4.12: Missouri River Channel Belt in the Mondamin and Herman Quadrangles (a) Allo-maps of Mondamin and Herman Quadrangles, (b) 1930s aerial survey of area mapped in part (a). Note the similarities in the highlighted areas.

CHAPTER 5

DISCUSSION

5.1 Tectonic Imprint on Missouri River Morphology

Prior to reaching the valley bottleneck in Sioux City, IA, the Missouri River is kept in its natural braided state where it hugs the southwest valley wall for the most part flowing in an East Southeast direction (Figure 5.1). In the Jefferson Quad, before reaching Sioux City, the Missouri is artificially modified to its channelized, meandering form. At Sioux City, the valley walls narrow down to approximately 6.4 kilometers wide then widen back south of the city (Figure 5.2). The southwest valley wall turns in a more southern direction west of Sioux City where the Missouri separates from the wall, crosses the narrow valley gap, hits the east wall of the Missouri Valley and is redirected southeast where is connects with the west Missouri Valley wall in the Salix Quadrangle.

The Missouri River continues to follow along the west valley wall for approximately 32 valley kilometers until it enters the Tekamah NW Quadrangle where the river valley turns an even more southerly direction going almost directly South before turning southeast again south of Herman, NE. At Tekamah NW, the river separates from the west valley wall (Figure 5.3a-b). From Tekamah NW on south out of Mondamin Quadrangle, the Missouri River flows south with its meander loops coming within 8 kilometers of hitting the East valley wall near Little Sioux, IA. The river eventually connects with the west wall again at Blair, NE, approximately 32 km north of Omaha.

A look at the allostratigraphic maps from Tekamah NW to Herman shows that along this stretch of river, the Missouri runs either touching or in close proximity to the western boundary of its channel belt (Figure 5.1a-b). The 4.8 to 6.4 km stretch of the modern meandering

Missouri flows right next to the edge of the channel belt near the southern end of the Tekamah NW Quad into the northern Tekamah Quad. A look at the pre-channelized Missouri in the 1930 aerial survey shows the Missouri pressed against its west channel belt boundary in Herman (Figure 5.4).

Other researchers (Leeder and Alexander, 1987; Holbrook and Schumm, 1999) have noted that rivers, under the influence of an active lateral tilting migrated laterally down-tilt and destroyed all meander cutoffs down-slope of the migrating channel leaving only meander cutoffs on the side up-dip of the shifted river. These authors also note that the river is forced toward the down-tilt side of the valley. If we look at the dimensions of the Missouri River channel belt (Figures 5.3a-b and Figure 5.5), it reaches widths of 16 or more kilometers wide and only once getting as narrow at 8 to 9.6 kilometers. Along the majority of its length, with few exceptions, the Missouri touches or stays in close proximity to its western belt south of Sioux City and its southern boundary west of Sioux City. Figures 5.5 illustrates that the Missouri meanders east, but all cutoffs (except for a short anomaly in the Tekamah NW, and Tekamah reach) are to the west. The entire channel belt east of the Modern Missouri is littered with channel cutoffs with their convex arcs pointing east or north and their channel arms terminating to the west or south with each successive loop getting progressively younger the closer they get to the western side of the belt. The river's migration down slope to the southwest has destroyed any loop cutoffs that formed to the west except for a large loop in the Tekamah NW Quadrangle. If left to its own devices, the Missouri would likely have eventually removed the Tekamah NW loop as well (Figure 5.3a).

The surficial deposits mapped in the Herman and Mondamin Quadrangles (Figure 4.7a) illustrate that the Missouri was working its way into the thick back swamp clay as recent as 80 years ago. This argues that the Missouri River is affected by lateral tilting of the river valley (Figure 5.4). The tilting is likely owing to the most recent retreat of the Laurentide Ice sheet. The Laurentide Ice Sheet reached into South Dakota and Iowa around 15 ka (Dyke and Prest, 1987; Forman and Pierson, 2002; Anderson et al, 2007) (Figure 5.5) though it didn't reach the stretch of valley in this study. The crust of the North American Continent subsided under the weight of the Laurentide Ice Sheet, but once it started to recede to the north with warming climate the crust would undergo uplift as it adjusted to the change (Figure 5.6). The ice sheet has long since retreated into northern Canada, but the glacial rebound, or uplift, of the crust requires thousands of years to adjust to the drastic decrease in mass. This would cause tilting of the valley over the span of the Holocene that rotated the valley floor in a direction away from the location of the ice sheet proper. The Missouri River appears to still be adjusting under the influence of the uplift as history of meander cut offs is consistent with the same tilting orientation caused by ongoing rebound (Leeder & Alexander, 1987; Holbrook, 1999; Peakall et al, 2000; Bridge 2003).

The Missouri River is being influenced by the lateral tilt of the Missouri River valley as it presses against the west wall of the valley and its own channel belt, but when we look at the Missouri River's channel belt, it's evident that the channel belt is also influenced by the lateral tilt of the valley. From the Yankton Quadrangle to the Tekamah NW Quadrangle, the Missouri River's channel belt presses against the south and west valley walls (Figures 5.1 & 5.3). Figure 5.1 shows the position of the channel belt pressing against the south wall with flat, featureless back swamp stretching from the northern channel belt boundary to the bedrock of the northern valley wall. Figure 5.3, shows a similar organization. The channel belt presses against the west valley wall, but to the east of the eastern belt boundary there is only large splay deposits and thick back swamp clays.

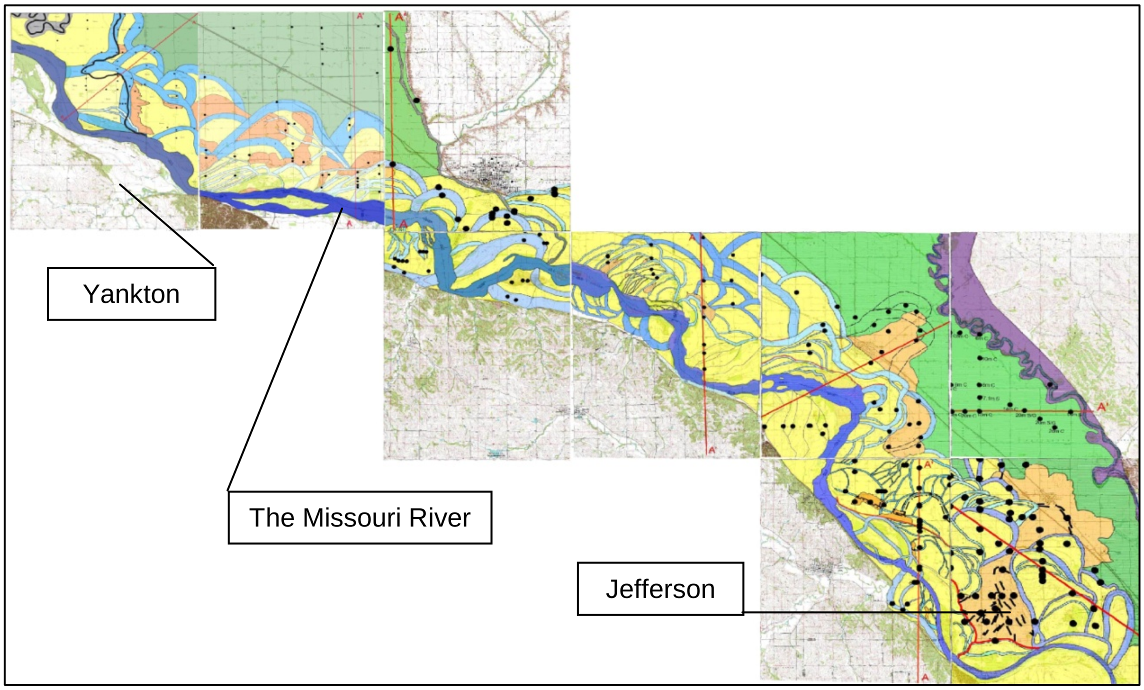


Figure 5.1: Allostratigraphic Maps form Yankton Quadrangle to Jefferson, SD.

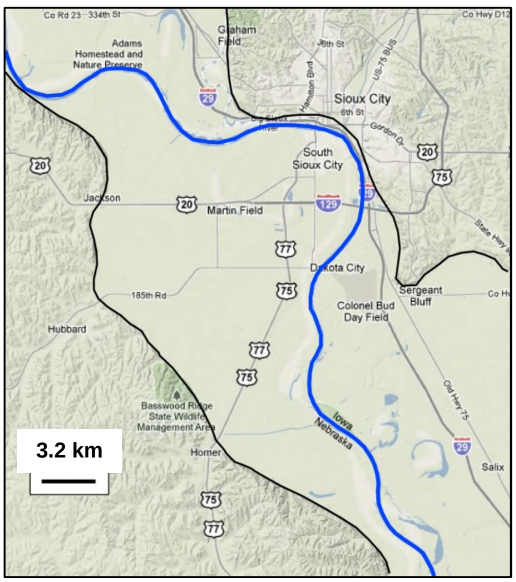
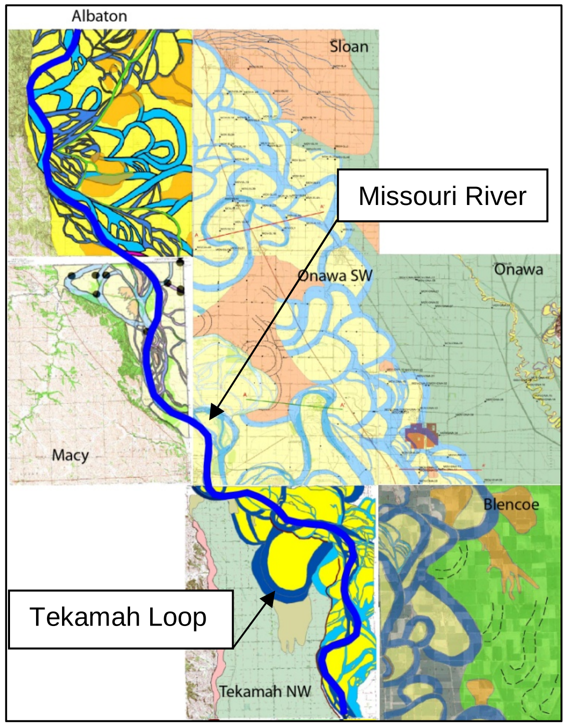
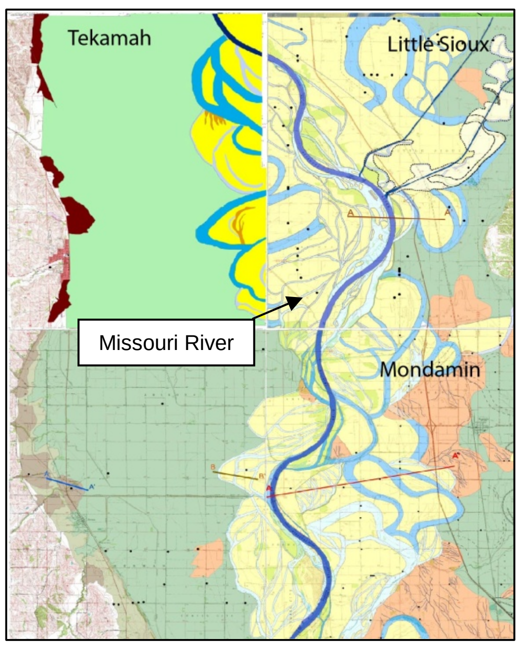


Figure 5.2: Terrain Map from Sioux City, NE to Salix, IA. Blue Line traces the Missouri, Black Lines trace valley wall boundaries. (Image: http://www.googlemaps.com)



(a)



(b)

Figure 5.3: Allostratigraphic Maps form Albaton Quadrangle to Mondamin Quadrangle (a) Albaton to Blencoe, (b) Tekamah to Mondamin. Each quadrangle represents 7.5 minutes of distance.

5.2 Goosenecks

The present day Missouri River is a naturally braided alluvial system. Preserved valley scars of old channel loops show the Missouri used to be a meandering system. Thresholds were reached that pushed the river to a braided system in recent history. The sediment capacity (Schumm & Khan, 1972; Bridge 2003) of the Missouri is one threshold variable and is substantial as indicated by the high sediment load the Missouri River contributes to the Mississippi River system even with continued human maintenance (Figure 5.7) (Moody et al, 2003; Meade & Moody, 2009).

Even in its braided state, the Missouri exhibits its ability to transition to a meandering state if only on a temporary basis. Numerous studies established how almost any obstruction can alter or divert water flow to form a more concentrated single-channel flow, be it changes in slope (Leopold and Wolman, 1957; Holbrook and Schumm, 1999; Holbrook et al, 2006), large wood debris (Daniels and Rhoads, 2003**;** Elliot and Jacobson, 2006), clay plugs of channel fills (Hudson & Kesel, 2000), vegetation (Hadley, 1961; Brice, 1964; Smith, 1976; Witt, 1985; Fielding et al, 1997; Huang & Nanson, 1997; Millar & Quick, 1998; Rowntree & Dollar, 1999; Gran & Paola, 2001; for review Bridge, 2003; Bridge, 2003; Camporeale et al, 2007; Braudick et al, 2009), or even just highly resistant cut bank material (Constatine et al, 2009). Any of these obstructions could impact a shallow, braided Missouri River with turbulent water flow and heavy with sediment (Leopold and Wolman, 1957). Once encountered, the obstruction could focus the water flow causing a temporary transition to a meandering state. Since the threshold conditions in the river favor braiding, the Missouri would transition back to braided once it was free of the barrier's influence (Figure 5.8). In the meantime, the river would be channelized in an energy state that exceeded normal meandering conditions and requiring sinuosity above the usually stable (c.f. Stolum, 1996; Hooke, 2007b). A development of a highly sinuous local runaway meander would be likely. A highly sinuous potential gooseneck meander would continue to develop, rotating upstream (Carson and Lapointe, 1983; Larsen, 1995) until cutoff and thus a return to its natural braided system. The effect of obstruction on conversion of the braided Missouri River to a meandering form is illustrated at two locations. A look at an allostratigraphic map of the Sioux City Quadrangle (Figure 5.9) also shows a large number of stacked hairpin/gooseneck loops to the west of the channel pointing up-dip. These occur where the river is forced to confinement as it impacts the narrow valley wall. If not for the forced stabilization by the U.S. Army Corps of Engineers, the Missouri River could continue to develop goosenecks and hairpins caused by the “immovable” valley wall. A similar situation is also evident in the mapped quadrangles in Missouri State (figure 5.10). The Missouri River is flowing west to east though a valley similar to the Nebraska/Iowa valley, but not as wide. The width of the valley shrinks to a span of approximately 3.2 kilometers wide. Observation of the allo-units in these two quads shows a “train wreck” of channels where the Missouri River is trying to meander, but is being force through a comparatively narrower valley where it is forced abruptly against a bedrock valley wall. The channel scars paint a repeated pattern of meander migration followed by cut off over and over again as the river whipped back and forth across the valley being forced down a funnel by obstructing valley walls.

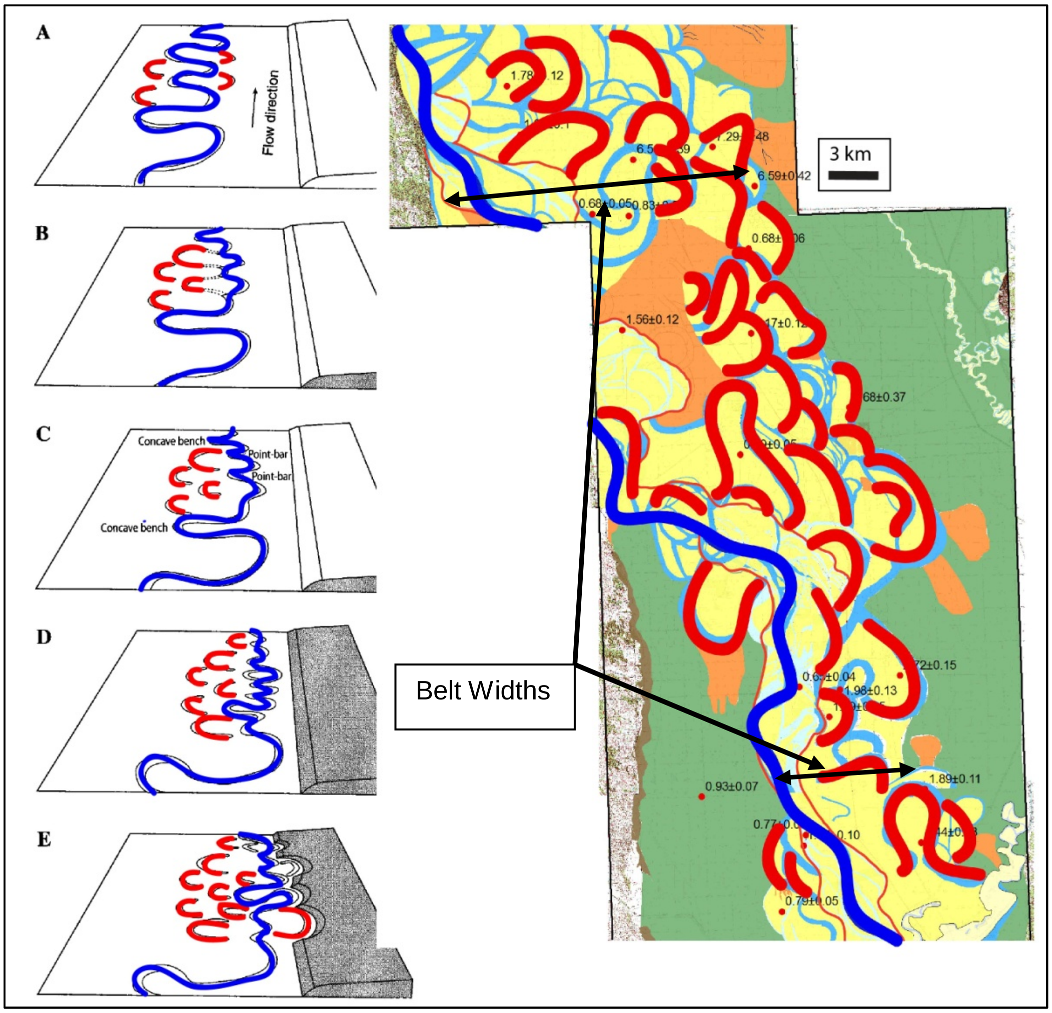


Figure 5.4: Effects of lateral valley tilting on rivers. (*Left*) Cross valley migration caused by ground tilting. (Peakall et al, 2005). (*Right*) The Missouri River channel belt mapped from Sloan, IA (north) to Little Sioux City (south). The belt reaches widths of over 16 kilometers

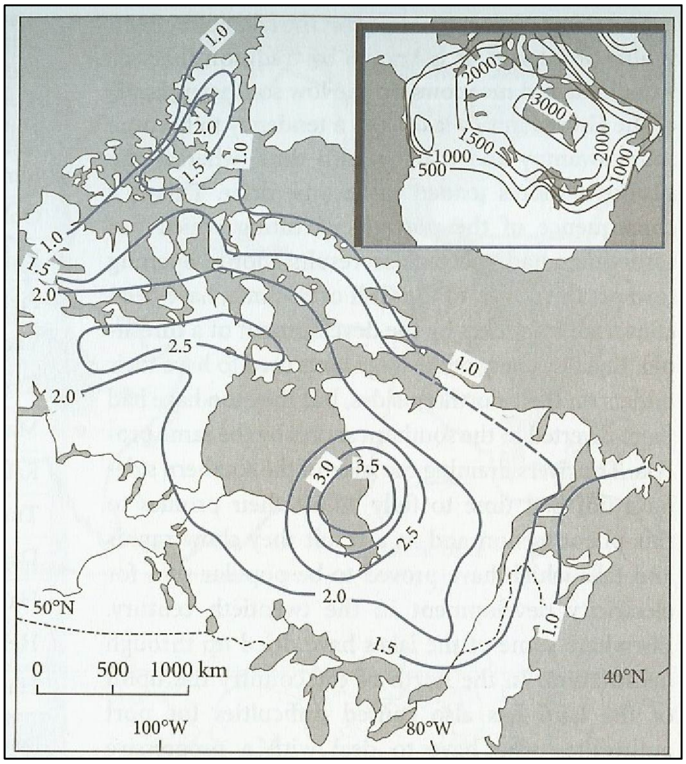


Figure 5.5: Average uplift rate during Holocene of North American. Uplift (meters) during glacial retreat. Inset: Thickness in meters of Laurentide Ice Sheet at 18,000 bp (Anderson et al, 2007).

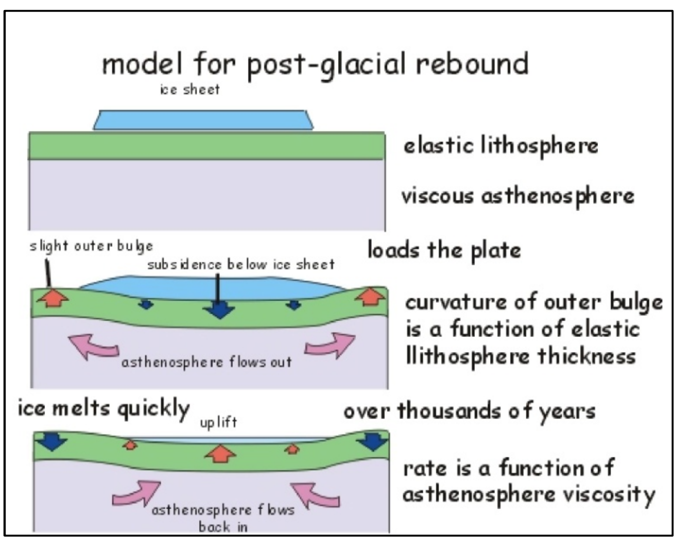


Figure 5.6: Model for glacial rebound. (http://www.see.leeds.ac.uk/structure/dynamicearth)

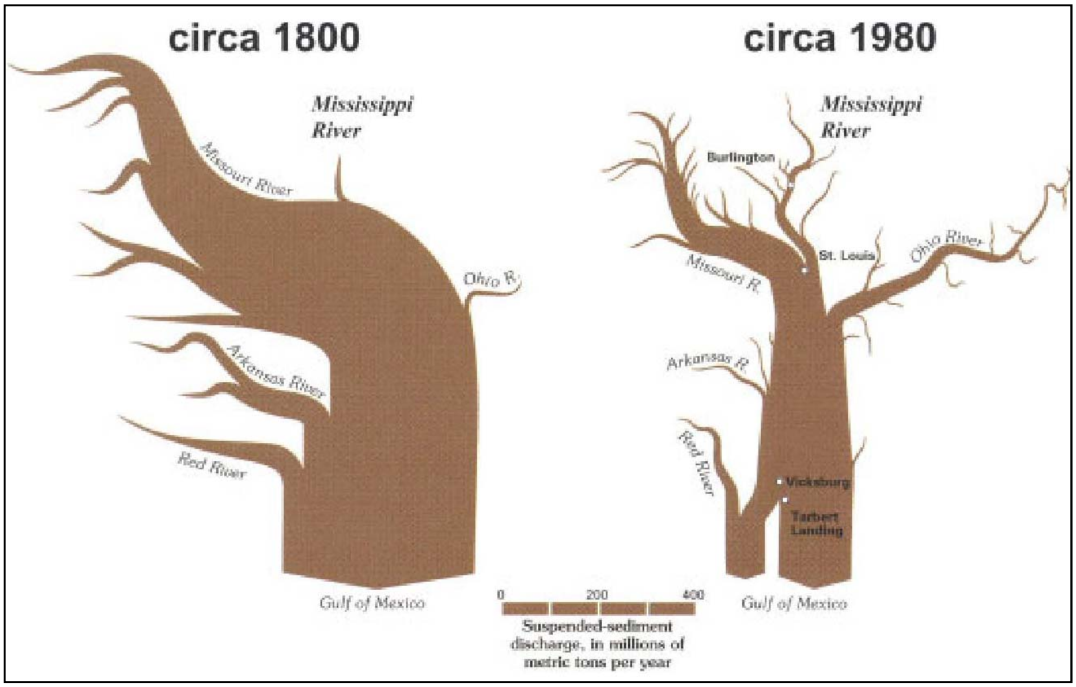


Figure 5.7: Sediment load of the Missouri River prior to (circa 1890) and post (1980) human development. The Missouri still provides 60% - 70% of the Mississippi's sediment load.

In the case of Sioux City and the Missouri River segment in Missouri State, obstacles, the bedrock valley wall, are constantly forcing the Missouri River to channelize and locally take on a meandering form. These valley walls are sustained obstacles that force the river to become meandering consistently and repeatedly at the same location. In the case of the gooseneck loops analyzed in this work, obstructions force a deviation (Leopold and Wolman, 1957) of the Missouri's natural braided state, even turning and migrating up-dip against the slope of the valley (Jackson, 1975; Carson & Lapointe, 1983; Larsen, 1995), but the deviation is just temporary and not consistently at a fixed location.

The separation of ages between the different gooseneck loops imply that the loops aren't related to each other. This means that one loop didn't create a domino effect encouraging the development of the others with one possible exception. The Sloan and Onawa SW Goosenecks are dated at around 100 years apart. The Sloan Gooseneck, at its youngest, is dated at 0.68 ka (+/- 0.05) and the Onawa SW Gooseneck is dated at 0.59 ka (+/- 0.05).

Both loops fall into the same time frame if we take the +/- 50 year error associated with both samples. Also, the Onawa SW OSL sample was taken in the middle of the loop, but the meander scroll pattern implies that if a sample was collected at the tip of the loop, we would have a much younger date. This indicates, depending on the actual age of the bar termination inside the Sloan Gooseneck, the Onawa SW loop could have initiated as a possible reaction to Sloan's extremely high sinuosity (sinuosity ratio = 7.7) and then been cut off at a more recent time. Otherwise, the goosenecks appear to originate independent of each other in time.

Based on the time gaps between the gooseneck loops, these braided transitions to meandering can occur at any time given the correct conditions. A look through the rest of the Missouri River Valley outside of the study area for additional meander style loops of this type reveals one further example before the valley narrows going into Omaha, NE, or at least a gooseneck preserved in its initial stage. East of De Soto, NE is the De Soto National Wildlife Refuge, which is bordered by the remnants of a gooseneck loop and the Modern Missouri. De Soto Lake is visible in modern aerial photography as an oxbow lake, but a look at the 1930s aerial survey clearly depicts this oxbow served as the active Missouri River route at least 80 years ago (Figure 5.11). De Soto Lake was manually cut off when the river underwent channelization by the U.S. Army Corp of Engineers (Hallberg et al, 1979). Since the De Soto loop is outside the Missouri Mapping project's focus area, there are no OSL or soil samples, but a look at the scroll patterns of the De Soto National Wildlife Refuge loops show the migration of the channel cutting up-dip to the north similar to the gooseneck loops analyzed in this work. There is no telling how this potential gooseneck loop would have developed had it been allowed to continue.

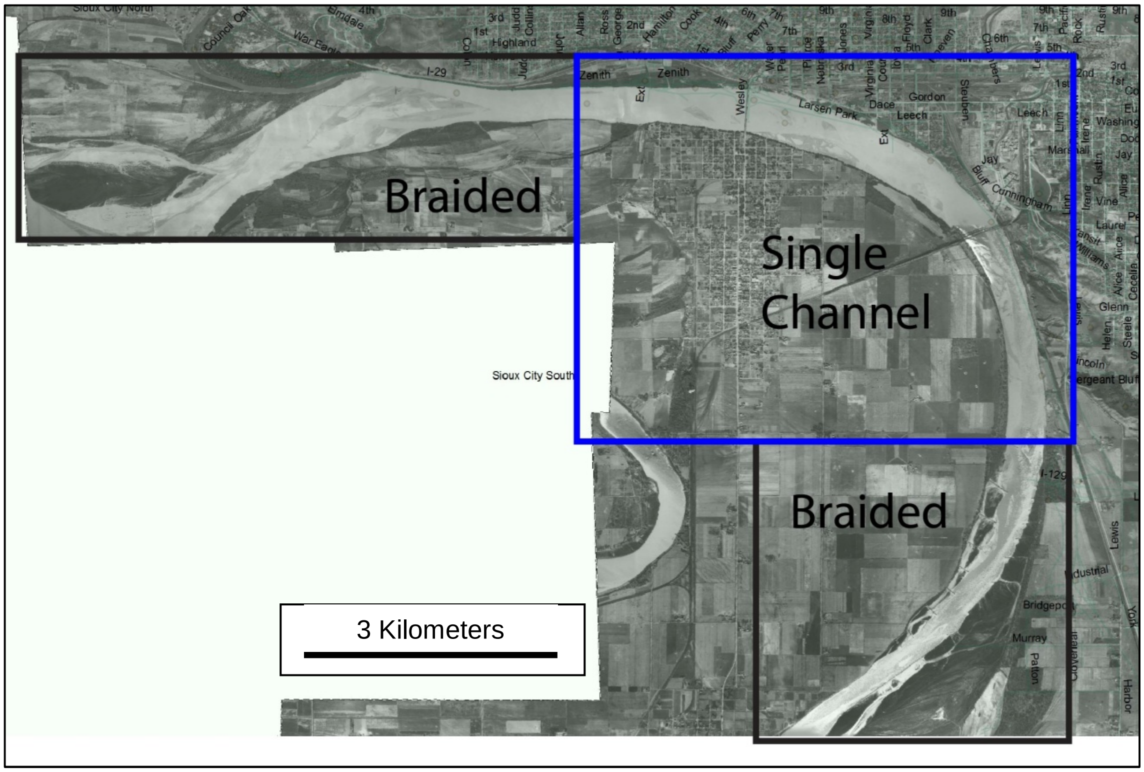


Figure 5.8: Missouri River transition between braided and single channel pattern. As the Missouri River is diverted south by the eastern wall of the Missouri River Valley, the channel pattern changes from braided to a single channel. Once free of the obstacle, it starts transitioning back to a braided pattern. Flow is west to east.

Though the high sinuosity of the goosenecks can be accounted for by local obstructions forcing meandering in a system beyond the stable meandering/braiding threshold, the shape of the goosenecks could be related to obstacles eroded on the floodplain proper (Leopold and Wolman, 1957). Clay pugs of channel fills (Hudson and Kesel, 2000; Hooke, 2004; Hooke, 2008) for instance could affect every gooseneck loop in this study. The Salix Gooseneck is cutting into 3 channel fills covered by 5 meters of splay that are linked to an old channel belt dated at 12.2 ka (Figure 5.12). The Sloan Gooseneck was migrating into 5 different channel fills to the east and up-dip to the north until the east arm of the channel eventually started migrating back to the west. The Onawa SW Gooseneck cuts into 5 channel fills; the Little Sioux loop cuts into one and the Mondamin loop terminates 3 channel fills to the north and east. Thick splays cover all of these channel fills except the Sloan Gooseneck. There is no splay material covering the channel fills butted up against the Sloan loop, but the southeast portion of the Sloan Gooseneck is pushed against a large splay that covers about a quarter of the Onawa SW Quad. The large splay in Onawa SW intersects three gooseneck events: 1) Sloan from the North, 2) the Onawa SW Gooseneck migrating into it from the south, and 3) braided channels cutting into the splay from the west. This splay adds thickness to the floodplain added resistance to erosion (Constatine et al, 2009; Parker et al, 2010).

The Missouri River transitioned from a natural meandering river to a natural braided state between 1.5 to 2 ka. All of the meander gooseneck events in this study, except the Little Sioux loop, are dated at less than 1 ka. The Little Sioux gooseneck is dated at less than 2 ka (1.44 +/- 0.08 ka). Despite being in a braided state, the Missouri River left behind evidence of continuing meandering events.

All of the loops, except the Little Sioux gooseneck, appear to be steered by these resistant strata on the floodplain and seek the more easily eroded, non-cohesive sand of their own point bars (Hook, 2007a; Hook, 2008; Constatine et al, 2009). This appears to be a dominant factor controlling the contorted shape of these loops. The Little Sioux Loop kept working north and southeast coming close to a neck cutoff. The Salix and Sloan loops rotate north and then west to cut into their point bars. The Mondamin Gooseneck eventually stopped migrating into the splays and channel fills to the northeast and east. Unlike the others, the Mondamin loop developed a second lobe (Brice 1974), which built off to the northwest through easier material while Bar 3 started chewing up its own sand bar into the gooseneck (Figure 5.13). The loops in general show a trend of modifying their shape during growth to permit growth into the least resistive floodplain material.

The Onawa SW Gooseneck has an interesting difference from the rest of the loops. The large splay in the Onawa SW Quad is on the northwest edge of the Onawa SW bend apex as well as the 3 channel fills discussed earlier, but to the east of the bend apex is the sandy point bar material on an older meander. Before whatever event resulted in this loop getting cutoff, the shape of the Onawa SW channel indicates that the head of the loop was rotating (Carson and Lapointe, 1983; Larsen, 1995) to the east into the eastern sand bar. The bend apex was rotating into the bar, while the east arm was pulling away from the eastern channel fills and eroded into its own point bar (Figure 5.14). If channel development had continued, the Onawa SW Gooseneck would likely be a gooseneck pointing east instead of west like the others.

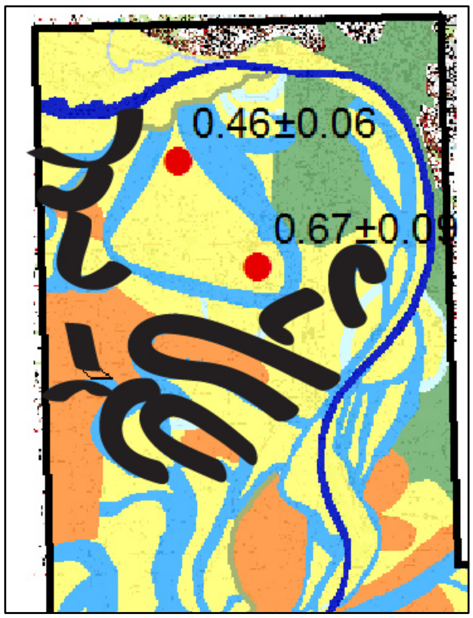


Figure 5.9: Meander “Train Wreck” in Sioux City Quadrangle. Quadrangles are 7.5 minutes distance.

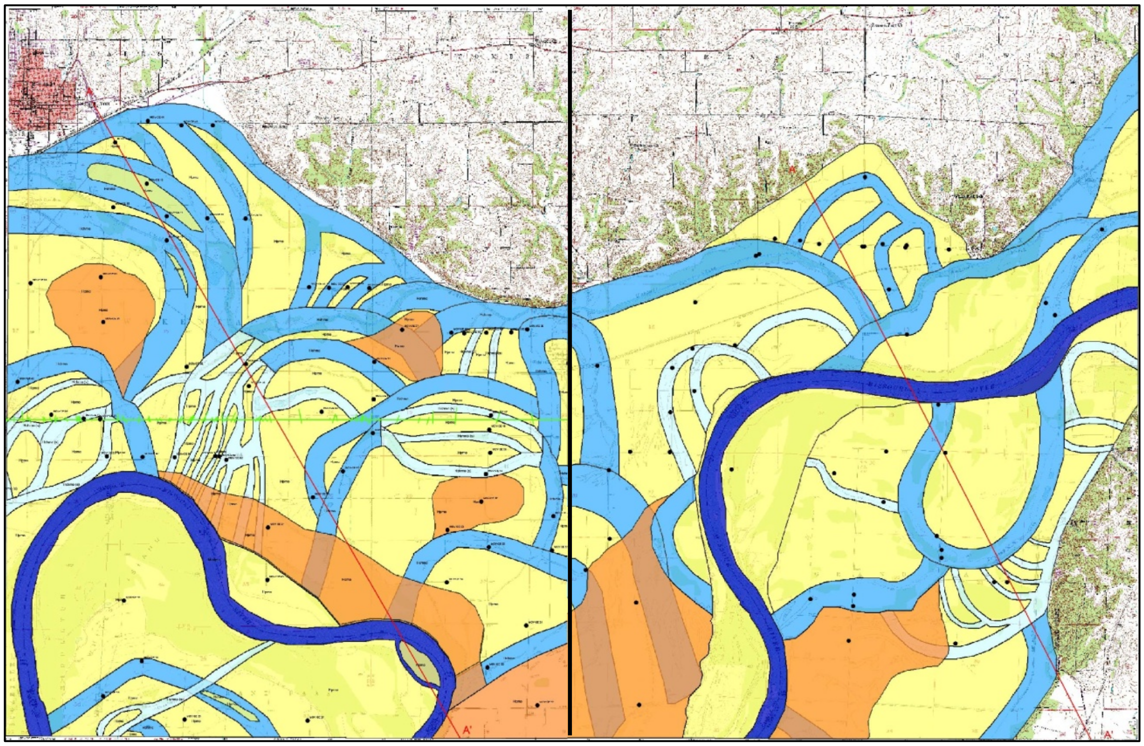


Figure 5.10: Carrolton East, MO (Left Quadrangle) and Miami Station, MO (Right Quadrangle). Quadrangles are 7.5 minutes distance.

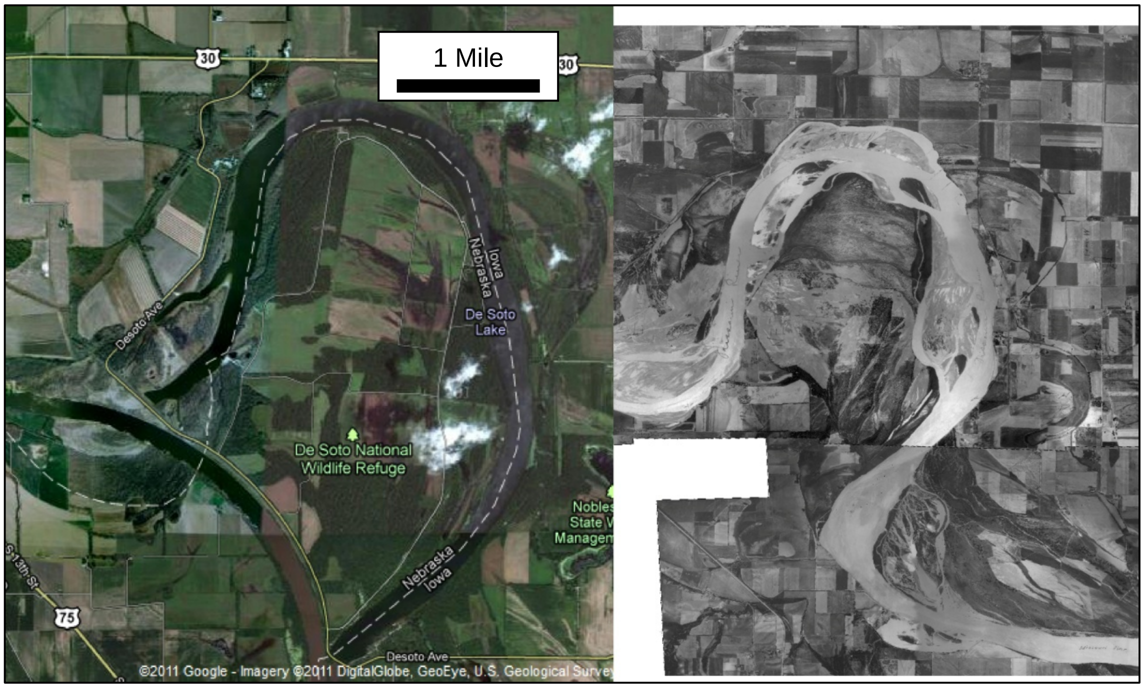


Figure 5.11: Modern day De Soto Lake versus 1930s De Soto river bend. (Left image: screenshot from Google Maps Satellite view; Right image: 1930s aerial survey)

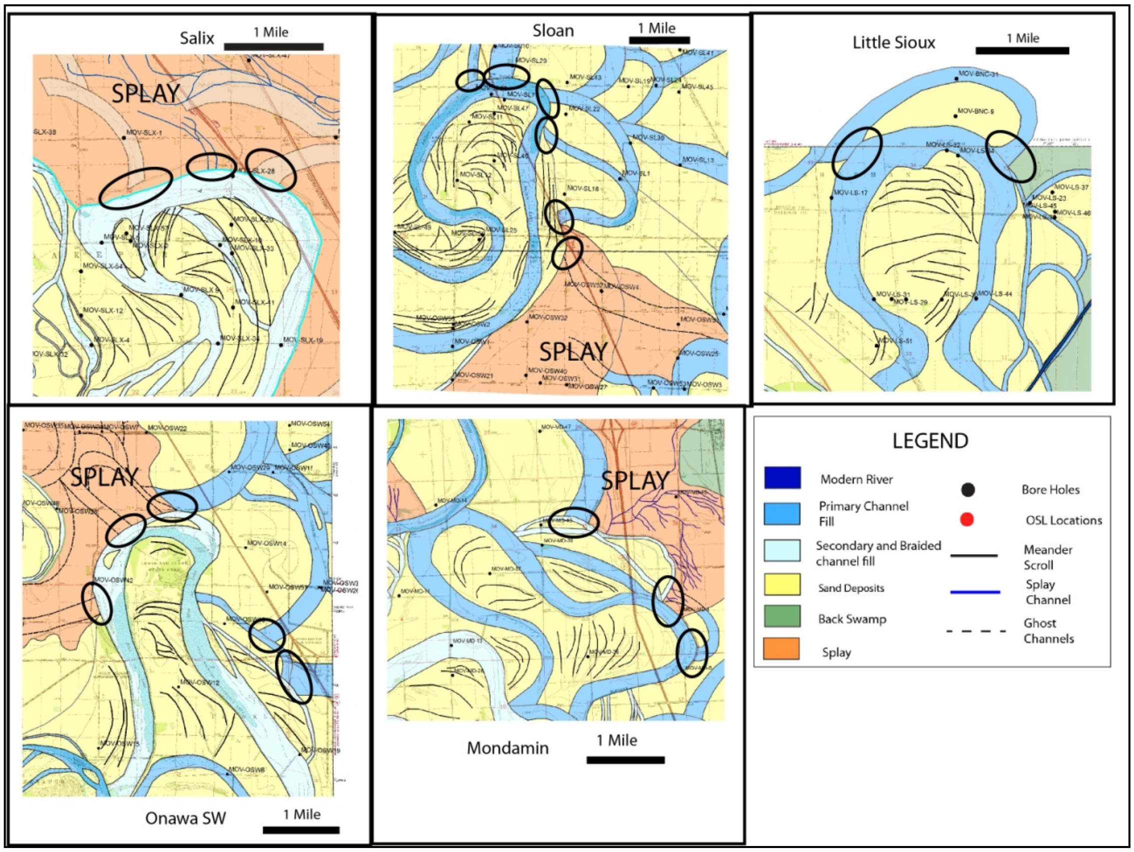


Figure 5.12: Splays and Channel Fills on Gooseneck Boundaries. Channel fill terminations are circled features. Dashed lines represent buried ghost channels.

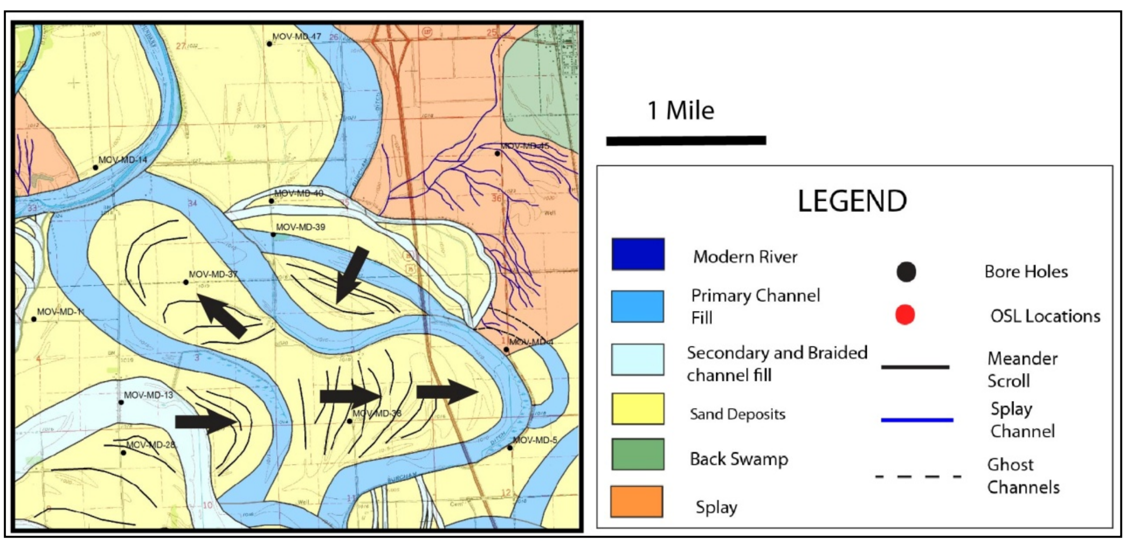


Figure 5.13: Mondamin Scroll Patterns

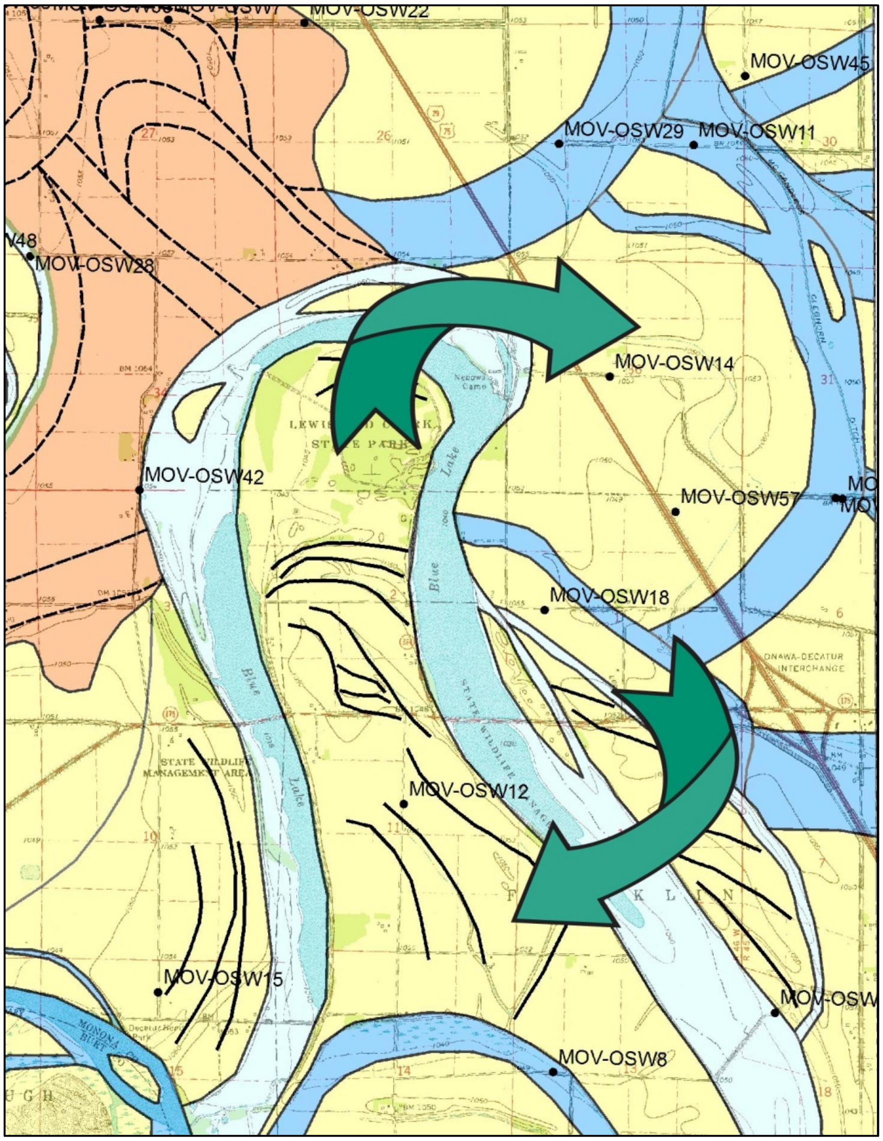


Figure 5.14: Onawa SW Gooseneck Loop Rotating East. As the east arm starts migrating back to the west, the head of the loop whips over the top to the

CHAPTER 6

CONCLUSIONS

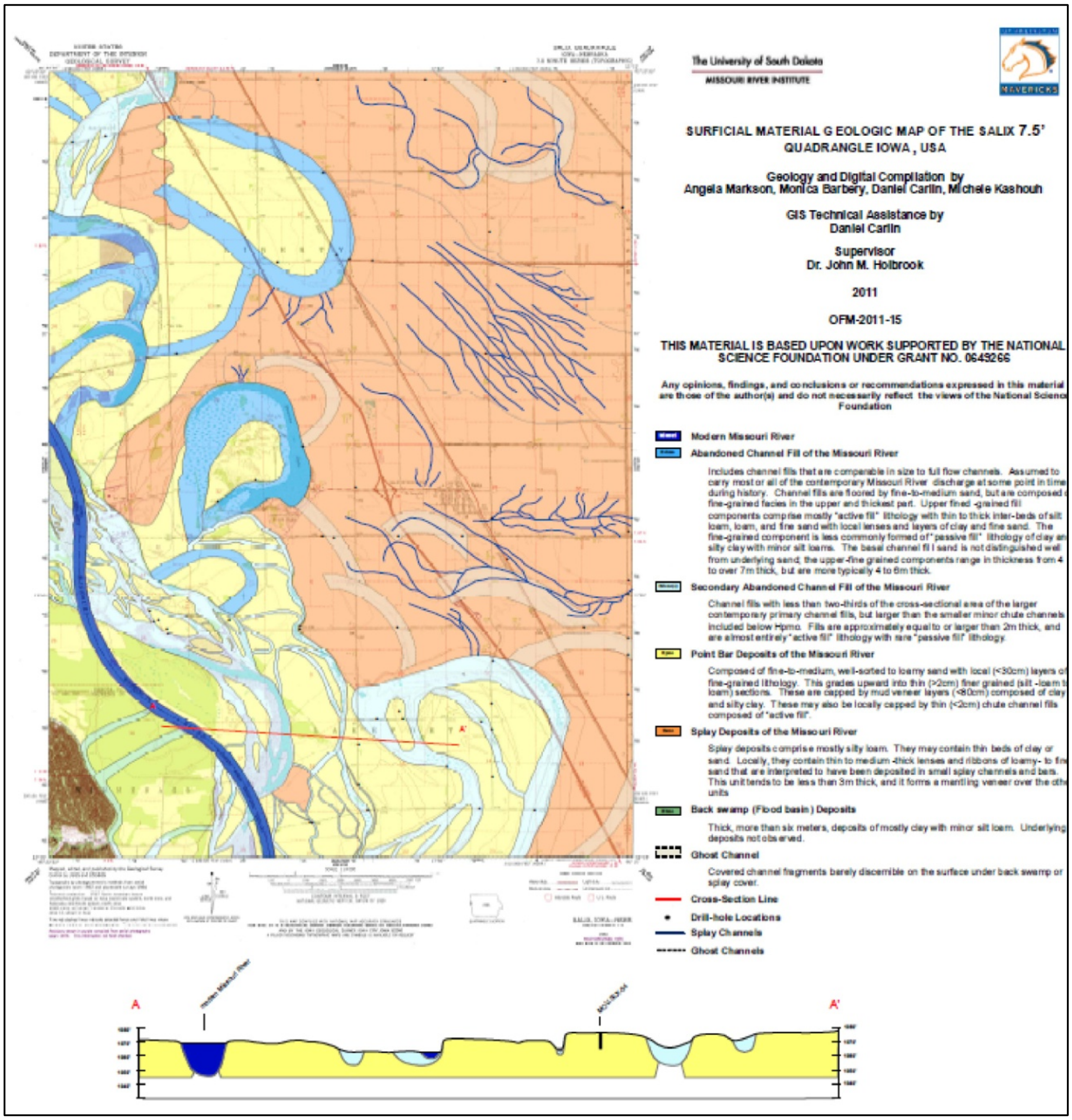
The lateral tilting of the Missouri River valley infers the presence of tectonic rebound, which has influenced the river's evolution over the Holocene. The gooseneck and other meander loops are overwhelmingly preserved on the up-tilt side of the valley floor of the Missouri River and appear to be the product of a fluvial system dominated by the western lateral tilt from tectonic uplift. The Laurentide Ice Sheet, which only came as close to the study area as South Dakota and central Iowa, has been absent in the region for at least the last 14 ka, but it has left a lasting impact on the morphology of the Missouri River.

The Missouri River is a naturally braided system that has exhibited its capacity to transition to a meandering pattern on a temporary and local basis and then just as quickly shift back to its braided state. Impact with bedrock valley walls and valley choke points serve as an obstruction, which may cause repeated transition from meandering to braided at these locations. This study argues that any number of natural obstacles can result in similar focusing of the flow and transition from braided river into a meandering pattern. This can initiate a runaway meander loop with the potential of turning up-dip possibly evolving into gooseneck loop. This process, once started maintains itself until the cutoff conditions are reached. In the case of the gooseneck loops researched in this study, the data would suggest that the meanders reached a super critical state that eventually resulted in chute cutoffs during a high period of water discharge, shortening its length and allowing the Missouri River to return to its natural braided state.

There appears to be no age relationship between the gooseneck loops except, possibly, the Sloan and Onawa SW loops. The lack of connection via time, including the De Soto loop, which is less than 100 years old, proves that these goosenecks could initialize at any time prior to human development and maintenance. The goosenecks also share no similar characteristics in shape, but they do share one common trait. All 5 gooseneck meanders preferentially eroded into sandy point bars and around less erosive floodplain strata, which helped to push them toward unusual shape.

APPENDIX A

QUADRANGLE MAPS AND CROSS SECTIONS



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MISSOURI RIVER INSTITUTE
SURFICIAL MATERIAL G EOLOGIC MAP OF THE SALIX 7.5' QUADRANGLE IOWA , USA
Geology and Digital Compilation by
Angela Markson, Monica Barbery, Daniel Carlin, Michele Kashouh
GIS Technical Assistance by
Daniel Carlin
Supervisor
Dr. John M. Holbrook
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Modern Missouri River
Abandoned Channel Fill of the Missouri River
Includes channel fills that are comparable in size to full flow channels. Assumed to carry most or all of the contemporary Missouri River discharge at some point in time during history. Channel fills are floored by fine-to-medium sand, but are composed of fine-grained facies in the upper and thickest part. Upper fined -grained fill components comprise mostly "active fill" lithology with thin to thick inter-beds of silt loam, loam, and fine sand with local lenses and layers of clay and fine sand. The fine-grained component is less commonly formed of "passive fill" lithology of clay and silty clay with minor silt loams. The basal channel fil l sand is not distinguished well from underlying sand; the upper-fine grained components range in thickness from 4 to over 7m thick, but are more typically 4 to 6m thick.
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Composed of fine-to-medium, well-sorted to loamy sand with local (<30cm) layers of fine-grained lithology. This grades upward into thin (>2cm) finer grained (silt -loam to loam) sections. These are capped by mud veneer layers (<80cm) composed of clay and silty clay. These may also be locally capped by thin (<2cm) chute channel fills composed of "active fill".
Splay Deposits of the Missouri River
Splay deposits comprise mostly silty loam. They may contain thin beds of clay or sand. Locally, they contain thin to medium -thick lenses and ribbons of loamy- to fine sand that are interpreted to have been deposited in small splay channels and bars. This unit tends to be less than 3m thick, and it forms a mantling veneer over the other units
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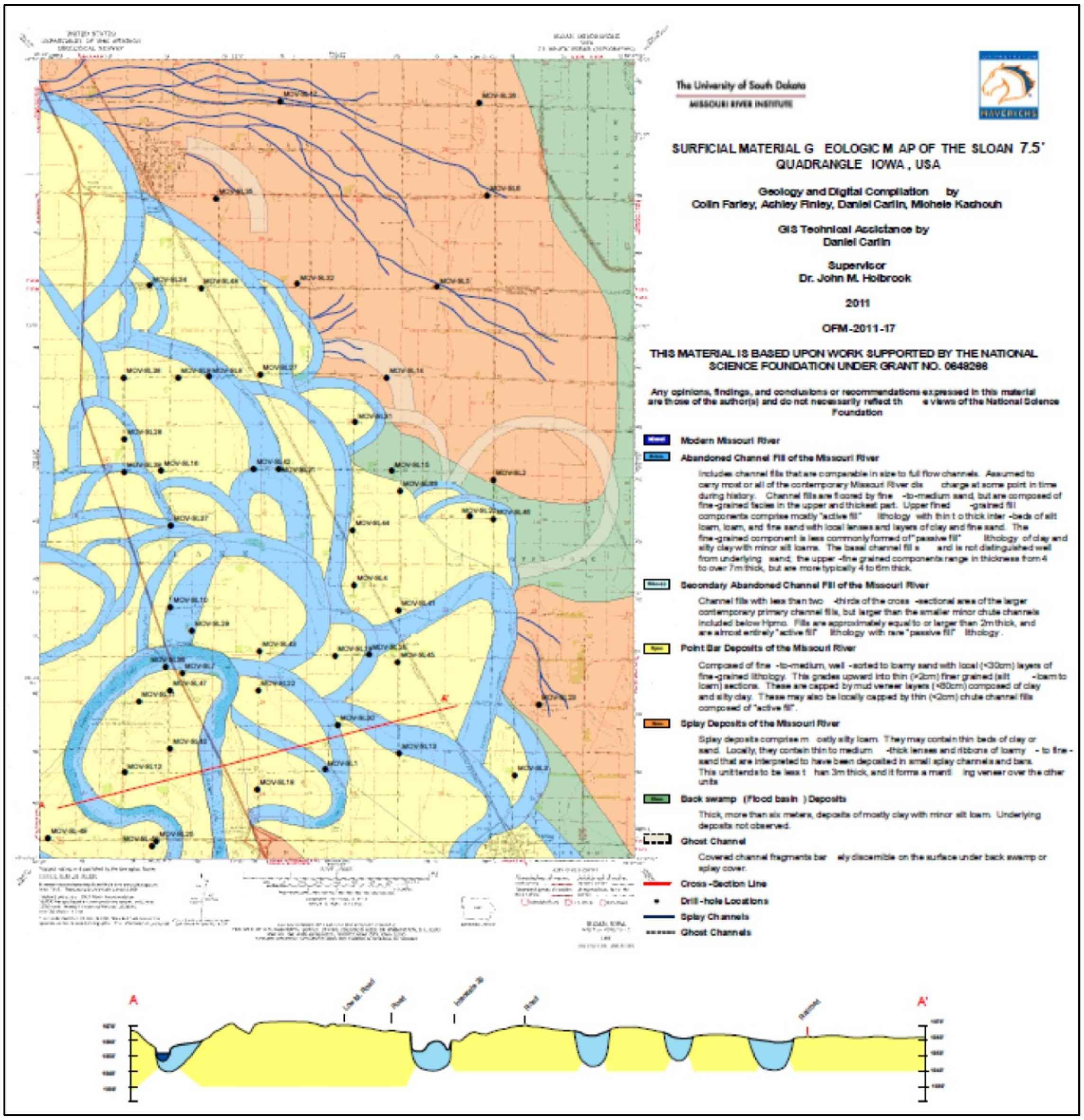
Ghost Channel
Covered channel fragments barely discernible on the surface under back swamp or splay cover.
Cross-Section Line
Drill-hole Locations
Splay Channels
Ghost Channels
A
A'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QUADRANGLE IOWA , USA
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Colin Farley, Achley Finley, Daniel Carlin, Michele Kachouh
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Drill -hole Locations
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Ghost Channels
A
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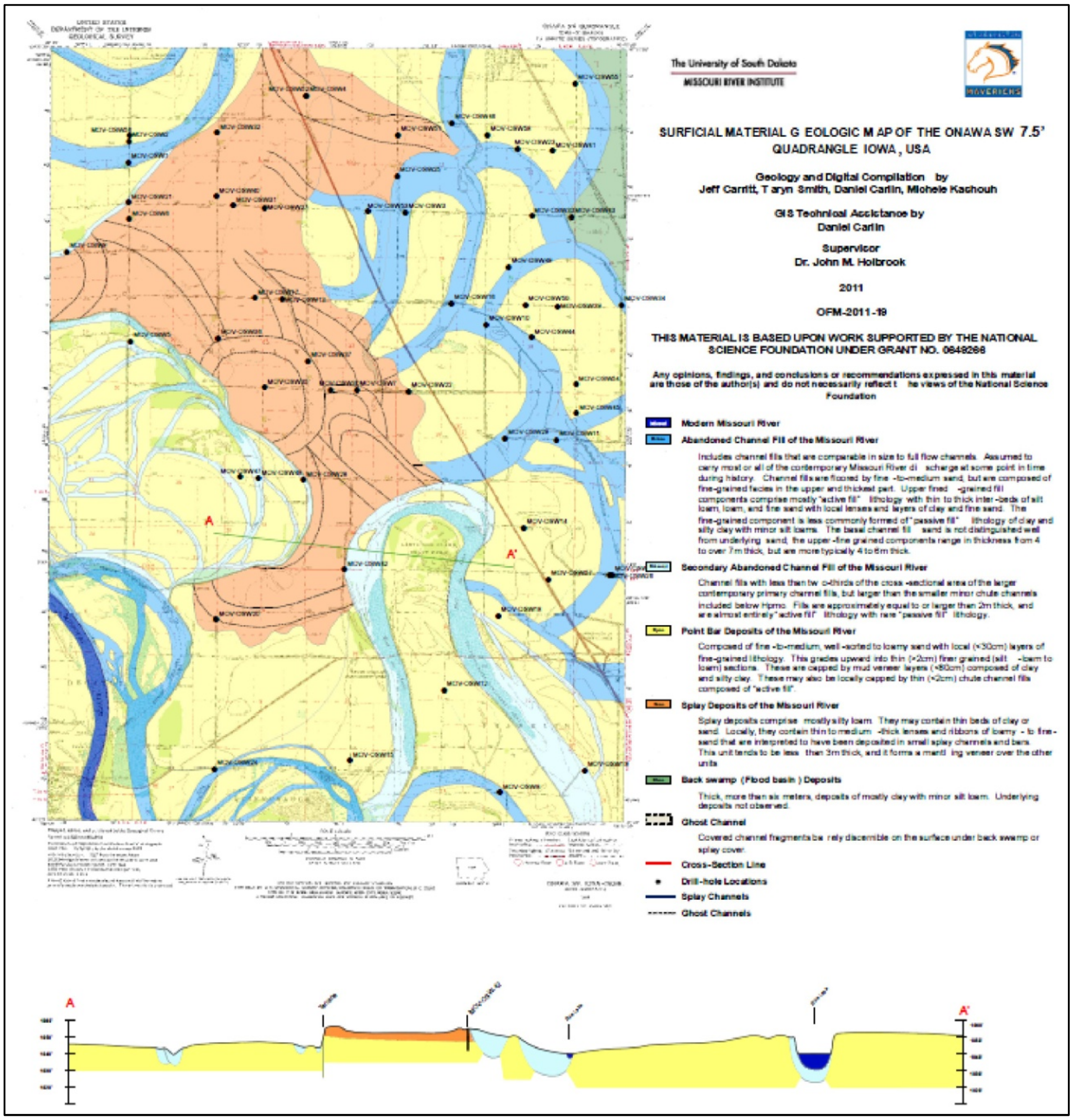
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Geology and Digital Compilation by
Jeff Carritt, T aryn Smith, Daniel Carlin, Michele Kachouh
GIS Technical Assistance by
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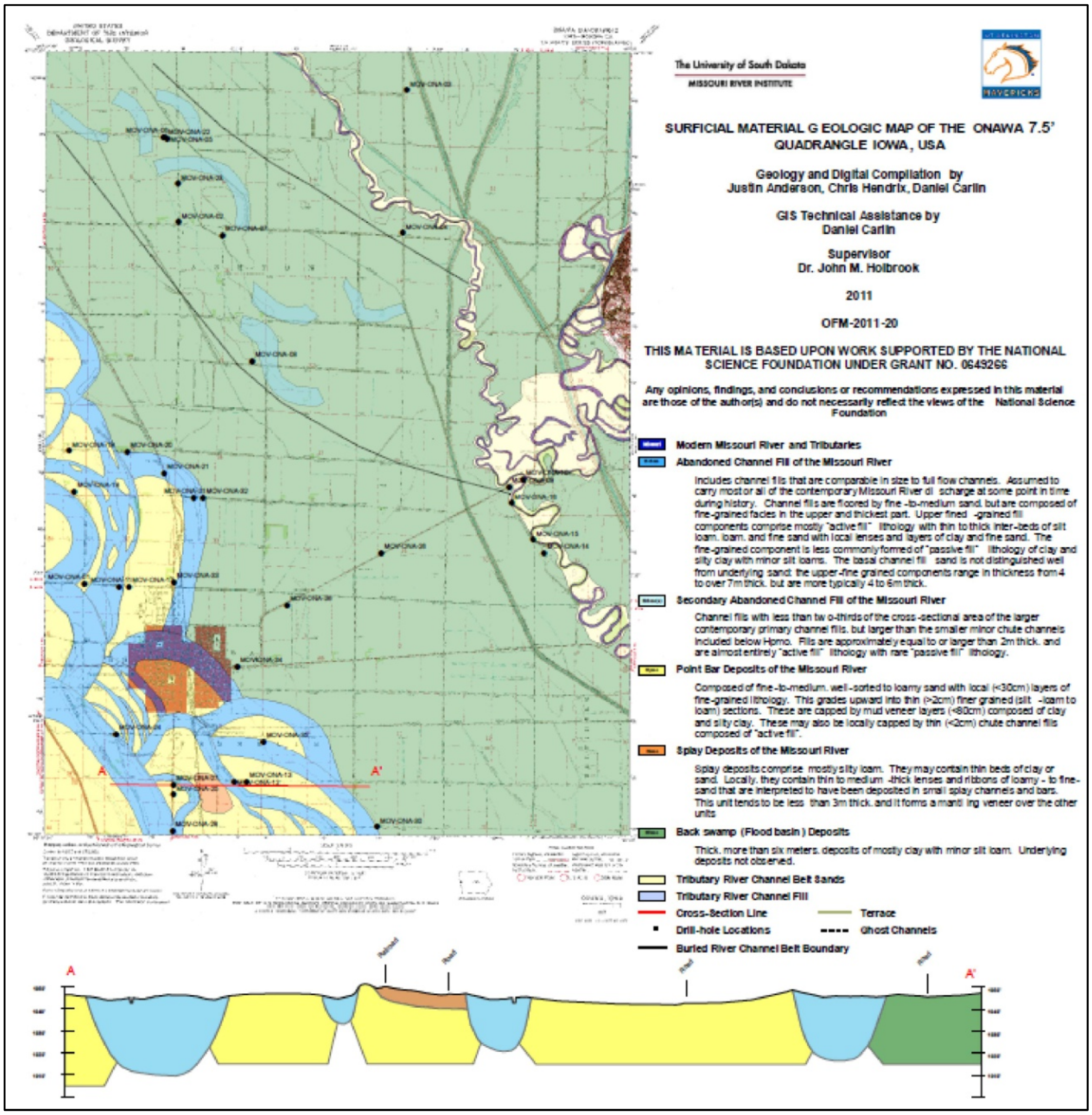
Ghost Channels
A
A'



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GIS Technical Assistance by
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Supervisor
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Tributary River Channel Belt Sands
Tributary River Channel Fill
Cross-Section Line
Terrace
Drill-hole Locations
Ghost Channels
Buried River Channel Belt Boundary
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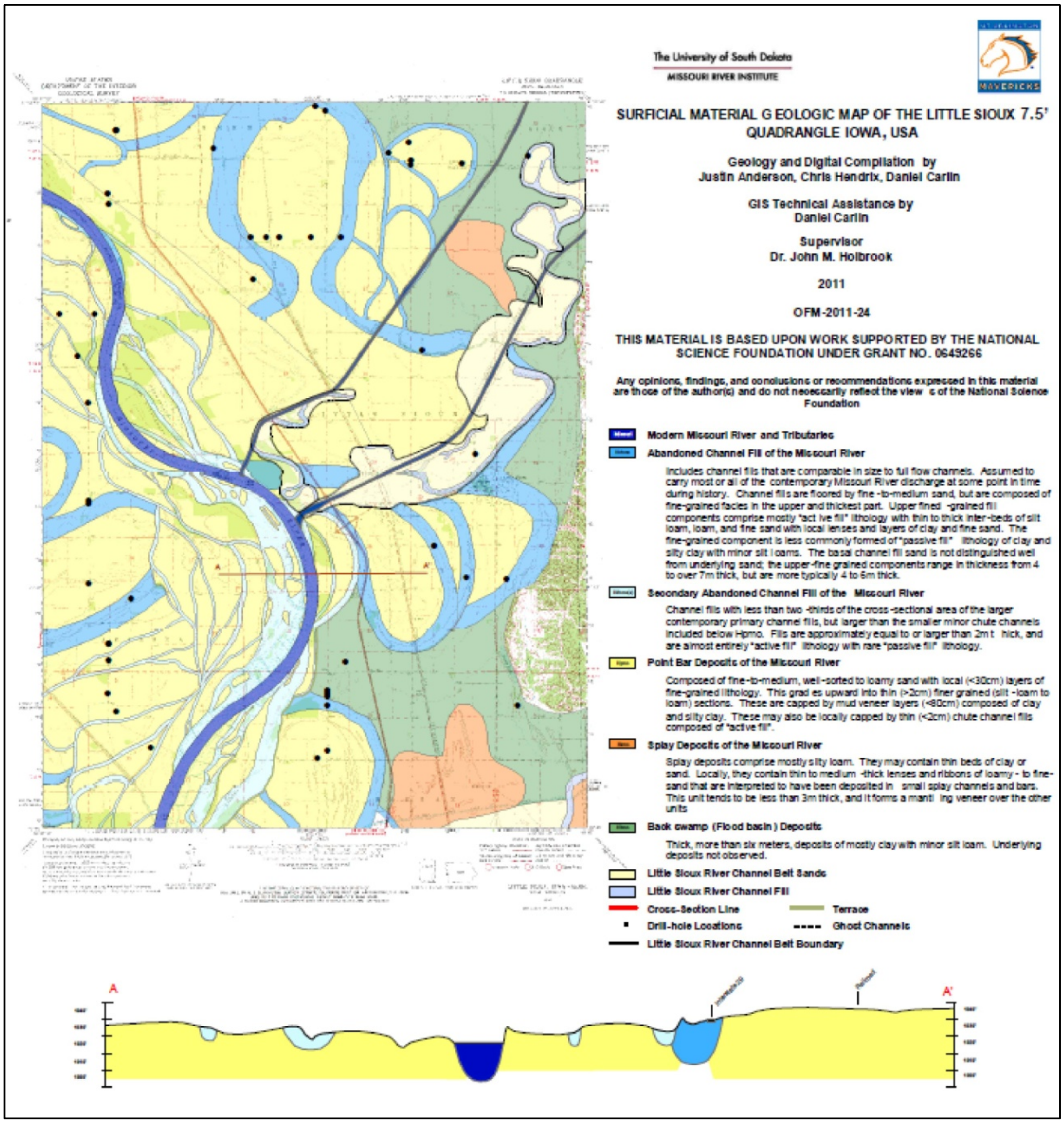
A'



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SURFICIAL MATERIAL G EOLOGIC MAP OF THE LITTLE SIOUX 7.5' QUADRANGLE IOWA, USA
Geology and Digital Compilation by
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Little Sioux River Channel Belt Sands
Little Sioux River Channel Fill
Cross-Section Line
Terrace
Drill-hole Locations
Ghost Channels
Little Sioux River Channel Belt Boundary
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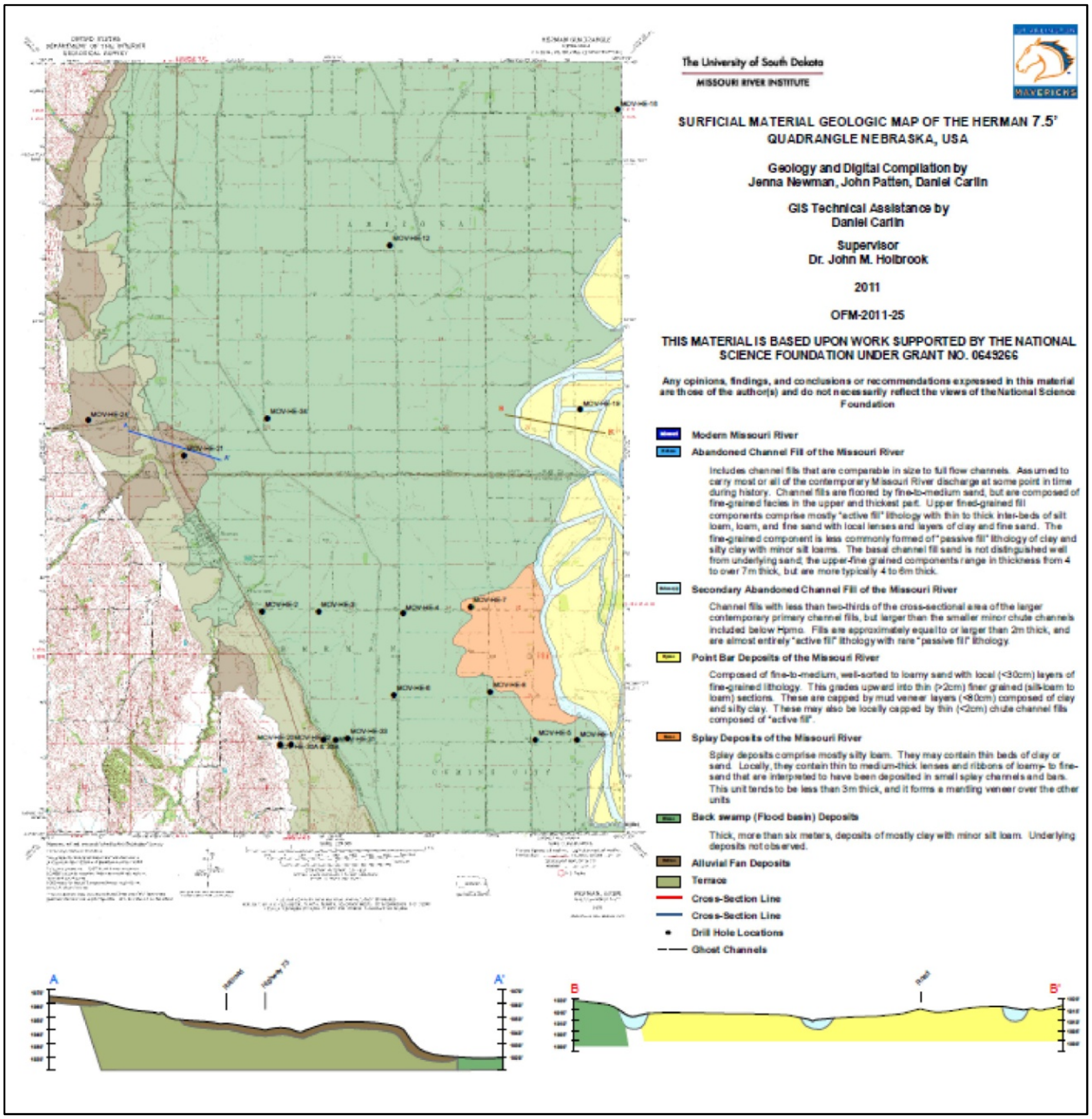
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SURFICIAL MATERIAL GEOLOGIC MAP OF THE HERMAN 7.5' QUADRANGLE NEBRASKA, USA
Geology and Digital Compilation by
Jenna Newman, John Patten, Daniel Carlin
GIS Technical Assistance by
Daniel Carlin
Supervisor
Dr. John M. Holbrook
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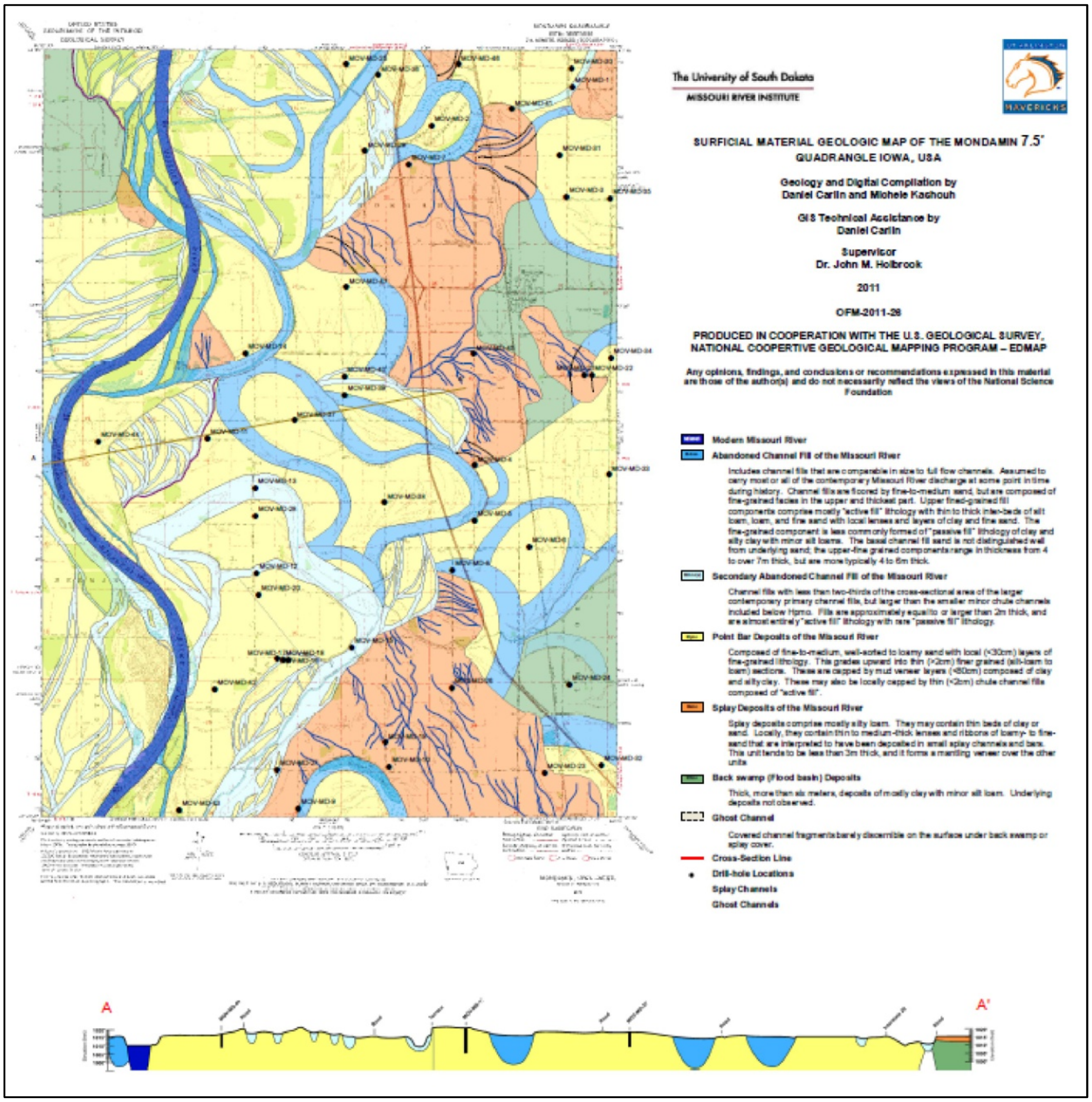
Alluvial Fan Deposits
Terrace
Cross-Section Line
Cross-Section Line
Drill Hole Locations
Ghost Channels
A
A'
B
B'


The University of South Dakota
MISSOURI RIVER INSTITUTE
MAVERICKS
SURFICIAL MATERIAL GEOLOGIC MAP OF THE MONDAMIN 7.5' QUADRANGLE IOWA, USA
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Modern Missouri River
Abandoned Channel Fill of the Missouri River
Includes channel fills that are comparable in size to full flow channels. Assumed to carry most or all of the contemporary Missouri River discharge at some point in time during history. Channel fills are floored by fine-to-medium sand, but are composed of fine-grained facies in the upper and thickest part. Upper fined-grained fill components comprise mostly "active fill" lithology with thin to thick inter-beds of silt loam, loam, and fine sand with local lenses and layers of clay and fine sand. The fine-grained component is less commonly formed of "passive fill" lithology of clay and silty clay with minor silt loams. The basal channel fill sand is not distinguished well from underlying sand; the upper-fine grained components range in thickness from 4 to over 7m thick, but are more typically 4 to 6m thick.
Secondary Abandoned Channel Fill of the Missouri River
Channel fills with less than two-thirds of the cross-sectional area of the larger contemporary primary channel fills, but larger than the smaller minor chute channels included below Hpmo. Fills are approximately equal to or larger than 2m thick, and are almost entirely "active fill" lithology with rare "passive fill" lithology.
Point Bar Deposits of the Missouri River
Composed of fine-to-medium, well-sorted to loamy sand with local (<30cm) layers of fine-grained lithology. This grades upward into thin (>2cm) finer grained (silt-loam to loam) sections. These are capped by mud veneer layers (<80cm) composed of clay and silty clay. These may also be locally capped by thin (<2cm) chute channel fills composed of "active fill".
Splay Deposits of the Missouri River
Splay deposits comprise mostly silty loam. They may contain thin beds of clay or sand. Locally, they contain thin to medium-thick lenses and ribbons of loamy- to fine-sand that are interpreted to have been deposited in small splay channels and bars. This unit tends to be less than 3m thick, and it forms a mantling veneer over the other units
Back swamp (Flood basin) Deposits
Thick, more than six meters, deposits of mostly clay with minor silt loam. Underlying deposits not observed.
Ghost Channel
Covered channel fragments barely discernible on the surface under back swamp or splay cover.
Cross-Section Line
Drill-hole Locations
Splay Channels
Ghost Channels
A
A'

APPENDIX B

BORE HOLE DATA

Abbreviations

C - Clay

SiL – Silty Loam

SiCL – Silty Clay Loam

L - Loam

SL- Sandy Loam

LS – Loamy Sand

fS – fine Sand

mS – medium Sand

cS – coarse Sand

S - Sand

NA – Not Applicable (Road Fill or Sample lost)

	MOV-SLX-1		MOV-SLX-2		MOV-SLX-5		MOV-SLX-9	
Depth meters	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation
0.1	SiL		LS		SiL		SiL	
0.2	SiL		LS		SiC		SiL	
0.3	SiL		L		SiC		SiL	
0.4	SiL		L		SiC		SiL	
0.5	SiL		SiCL	**Overbank Fines**	SiC		SiL	
0.6	SiL		SiCL		SiC		SiL	
0.7	SiL		L		SiC		SiL	
0.8	SiL		SiCL		SiC		SiL	
0.9	SiC		L		SiC		SiL	
1	SiC		fS		SiC		SiL	
1.1	C		fS		SiC		SiL	
1.2	SiL		fS		SiC		SiL	**Channel Fill**
1.3	SiL	**Splay**	fS		SiC	**Channel Fill**	SiL	
1.4	SiL		fS		SiC		SiL	
1.5	L		fS		SiC		C	
1.6	L		fS		L		C	
1.7	SiL		fS	**Bar Sands**	L		C	
1.8	SiCL		fS		L		C	
1.9	SiL		mS		C		SiC	
2	SiC		mS		SiC		SiC	
2.1	SiL		mS		SiC		SiL	
2.2	SiL		mS		SiC		L	
2.3	SiL		mS		SiC		L	
2.4	SiL		mS		L		SL	**Channel Bottom**
2.5	SiC		mS	**Bar**	L		SL	

	MOV-SLX-1		**MOV-SLX-2**		**MOV-SLX-5**		**MOV-SLX-9**	
Depth meters	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation
2.6	SIC				L		fS	
2.7	C				SiL		fS	
2.8	C				SiL		fS	
2.9	C				SiL		mS	
3	C				SiL		mS	
3.1	C				SiL		mS	
3.2	C				SiL		mS	**Channel Bottom**
3.3	C				SiL		mS	
3.4	C				SiL		mS	
3.5	C				SiL	**Channel Fill**	mS	
3.6	C				SiL		mS	
3.7	C				SiL		mS	
3.8	C	**Channel Fill**			SiL		mS	
3.9	C				L		mS	
4	SiC				SL		mS	**Channel**
4.1	SiC				SiC			
4.2	SiC				C			
4.3	C				SiC			
4.4	SiL				SiC			
4.5	SiL				SL			
4.6	L				SL			
4.7	SiL				LS	**Channel Bottom**		
4.8	SiL				LS			
4.9	SiL				LS			
5	SiC				fS			

	MOV-SLX-1		MOV-SLX-2		MOV-SLX-5		MOV-SLX-9	
Depth meters	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation
5.1	SiL				fS			
5.2	SiL				fS			
5.3	SiL				LS			
5.4	SiL				LS			
5.5	SiL				SiC			
5.6	SiL	**Channel Fill**			fS	**Channel Bottom**		
5.7	SiL				fS			
5.8	SiL				fS			
5.9	SiL				fS			
6	SiL				fS			
6.1	SiC				fS			
6.2	SiC	**Channel**			fS	**Channel**		
6.3								
6.4								
6.5								
6.6								
6.7								
6.8								
6.9								
7								
7.1								
7.2								
7.3								
7.4								
7.5								

	MOV-SLX-10		MOV-SLX-13		MOV-SLX-19		MOV-SLX-20	
Depth meters	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation
0.1	L		SiL		SiL		SiC	
0.2	SiL		SiL		SiL		SiC	
0.3	SiL		SiC		SiL		SiC	**Overbank Fines**
0.4	SiC		SiC		SiL		SiC	
0.5	SiL		SiC		SiL		L	
0.6	SiC		SiC		SiL		LS	
0.7	SiL		SiC		SiL		LS	
0.8	SiL		SiC		SiL		S	
0.9	C		SiC		SiL		S	
1	C		SiC		SL		S	
1.1	C		SiC		SiL		S	
1.2	C		SiC		SiL		S	
1.3	SiL	**Active Channel Fill**	SiC	**Channel Fill**	SiL	**Channel Fill**	S	**Bar Sands**
1.4	SiL		SiC		SiL		S	
1.5	SiL		SiC		SiL		S	
1.6	L		SiC		SiC		S	
1.7	SiL		SiC		SiL		S	
1.8	SiL		SiC		SiL		S	
1.9	SiL		SiC		SiC		S	
2	L		SiC		SiC		S	
2.1	SL		SiC		SiC		S	
2.2	SL		SiC		SiC		S	**Bar**
2.3	LS		SiC		SiC			
2.4	LS		SiC		SiC			
2.5	LS		SiC		SiC			

	MOV-SLX-10		MOV-SLX-13		MOV-SLX-19		MOV-SLX-20	
Depth meters	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation
2.6	fS	**Active Channel Fill**	L	**Channel Fill**	SiC	**Channel Fill**		
2.7	LS		SiC		SiC			
2.8	L		SiC		SiC			
2.9	L		SiC		SiC			
3	L		SiC		SiC			
3.1	SL		SL		SiC			
3.2	L		L		SiC			
3.3	L		SL		NA	**Samples Lost**		
3.4	L		SL		NA			
3.5	SiL		SiC		NA			
3.6	L		SiC		NA			
3.7	SL		SiC		NA			
3.8	L		SiC		NA			
3.9	L		SiC		NA			
4	L		SiC		NA			
4.1	SL		L		SiL	**Channel Fill**		
4.2	L		SiC		SiL			
4.3	L		SiC		L			
4.4	L		SiC		SiL			
4.5	L		C		SiL			
4.6	L		SiC		L			
4.7	SL		SiC		LS	**Channel Bottom**		
4.8	fS	**Bar Sands**	SiC		LS			
4.9	fS		C		LS			
5	fS		SiC		LS			

	MOV-SLX-10		MOV-SLX-13		MOV-SLX-19		MOV-SLX-20	
Depth meters	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation
5.1	L	**Bar Sands**	SiC	**Channel Fill**	fS			
5.2	L		SiC		fS	**Channel**		
5.3	fS		SiC					
5.4	fS		SiC					
5.5	fS	**Chute Channel**	SiC					
5.6	fS		SiC					
5.7			SiC					
5.8			SiC					
5.9			SiC					
6			SiC	**Channel**				
6.1								
6.2								
6.3								
6.4								
6.5								
6.6								
6.7								
6.8								
6.9								
7								
7.1								
7.2								
7.3								
7.4								
7.5								

	MOV-SLX-28		MOV-SLX-33		MOV-SLX-34		MOV-SLX-41	
Depth meters	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation
0.1	L		L		RF		SiL	
0.2	SL		L		RF	**Road Fill**	L	
0.3	SL		L		RF		SiL	
0.4	SL		SL		RF		SiL	
0.5	SL		LS		SL		SiL	
0.6	LS		LS		SL		L	
0.7	SL		LS	**Active Channel Fill**	SL		L	
0.8	L		fS		SL		L	
0.9	SiL		fS		SL		L	
1	SiL		LS		SL		L	**Overbank Fines**
1.1	SiC		SL		SiL		SiL	
1.2	SiC		SL		SiL		SiL	
1.3	SiC	**Channel Fill**	L		SiL		L	
1.4	SiC		L		SiL		SiL	
1.5	SiL		LS		SiL	**Channel Fill**	L	
1.6	SiC		fS		SiL		L	
1.7	SiC		LS		SiL		L	
1.8	SiC		LS		SiL		LS	
1.9	SiC		LS		SiL		L	
2	SiC		fS	**Bar Sands**	SiL		L	**Bar**
2.1	SiC		fS		SiL			
2.2	SiC		fS		SiL			
2.3	SiC		fS		SiL			
2.4	SiC		fS		SiL			
2.5	C		LS		SiC			

	MOV-SLX-28		MOV-SLX-33		MOV-SLX-34		MOV-SLX-41	
Depth meters	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation
2.6	C		LS		SiL			
2.7	C		SL		SiL			
2.8	C		SL		SiL			
2.9	C		SL		SiL			
3	C		LS		SiL			
3.1	SiC		L		SiL			
3.2	SiC		fS		SiL	**Channel Fill**		
3.3	C		fS		SiL			
3.4	C		fS	**Bar Sands**	SiC			
3.5	SiL		fS		SiC			
3.6	SiL		fS		SiC			
3.7	SiL		fS		SiL			
3.8	SiL	**Channel Fill**	fS		SiC			
3.9	SiC		fS		SiC	**Channel**		
4	SiC		fS					
4.1	C		LS					
4.2	SiC		S					
4.3	C		S	**Chute Channel over Point Bar**				
4.4	C		S					
4.5	C							
4.6	C							
4.7	C							
4.8	C							
4.9	SiC							
5	SiC							

	MOV-SLX-28		MOV-SLX-33		MOV-SLX-34		MOV-SLX-41	
Depth meters	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation
5.1	SiC							
5.2	SiC							
5.3	SiC							
5.4	SiC							
5.5	SiC							
5.6	SiC							
5.7	SiC							
5.8	SiC							
5.9	SiC							
6	SiC							
6.1	SiC							
6.2	SiC	**Channel Fill**						
6.3	SiC							
6.4	SiC							
6.5	SiC							
6.6	SiC							
6.7	SiC							
6.8	SiC							
6.9	SiC							
7	SiC							
7.1	SiC							
7.2	C							
7.3	SiC							
7.4	SiC	**Channel**						
7.5								

	MOV-SLX-42		MOV-SLX-46		MOV-SLX-48		MOV-SLX-50 (OSL)	
Depth meters	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation
0.1	SL		SiL		L		L	
0.2	SL		SiL		L		SiL	
0.3	L		SiL		SiL		SiL	
0.4	SiL		SiL		SiL		SiL	
0.5	SiL		SiL		SiL		SiL	
0.6	SiL		SiL		SiL		SiL	
0.7	L		SiL		SiL		SiL	
0.8	SL		SiL		SiL		SiL	
0.9	SL		SiL		SiL		SiL	
1	SL		SiL		SiL		SiL	
1.1	SL		SL		SiL		SiL	
1.2	SL		SL		SiL		SiL	
1.3	SL	**Splay**	SL	**Splay**	SiL	**Splay**	SiL	**Splay**
1.4	SL		SL		SiL		SiC	
1.5	SL		SL		SiL		SiL	
1.6	SL		SL		SiL		SiC	
1.7	SL		SL		SiL		SiL	
1.8	SL		SL		SiL		SiC	
1.9	SiL		SL		SiL		SiL	
2	SiC		SL		SiL		SiL	
2.1	SiL		SL		SiL		SiL	
2.2	SiL		SL		SiL		SiL	
2.3	SiC		SL		SiL		SiL	
2.4	SiC		SL		SiL		SiL	
2.5	SiC		L		SiL		SiL	

	MOV-SLX-42		MOV-SLX-46		MOV-SLX-48		MOV-SLX-50 (OSL)	
Depth meters	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation
2.6	SiL		SiL		SiL		SiL	
2.7	SiC		SiL		SiL		SiL	
2.8	SiC		L		SiL		SiL	
2.9	SiL		SiL		SiL		SiL	
3	SiC		SiL		SiL		SiL	
3.1	SiL		SiL		SiL		SiL	
3.2	SiC		SiL		SiL		L	
3.3	SiC		SiL		SiL		SL	
3.4	SiC		SiL		SiL		SL	
3.5	SiC	**Splay**	L		SiL		SL	
3.6	SiC		L		SiL		LS	
3.7	SiC		SiL	**Splay**	SiL		LS	
3.8	SiL		SiL		SiL	**Splay**	LS	**Splay**
3.9	SiL		SiL		SiL		LS	
4	SiL		SiL		SiL		LS	
4.1	SiL		SiL		SiL		LS	
4.2	SiL		SiL		SiL		LS	
4.3	L		SiL		SiL		LS	
4.4	fS		SiL		SiL		LS	
4.5	fS		SiL		SL		LS	
4.6	fS	**Splay**	SiL		SiL		LS	
4.7			SiL		SiL		LS	
4.8			SiL		SiL		LS	
4.9			SiL		SiL		LS	
5			SiL	**Channel**	SiL		LS	

	MOV-SLX-42		MOV-SLX-46		MOV-SLX-48		MOV-SLX-50 (OSL)	
Depth meters	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation
5.1					SL		LS	
5.2					SL		LS	
5.3					fS		LS	**Splay**
5.4					fS		LS	
5.5					fS	**Bar Sands**	LS	
5.6					fS		S	**Bar Sands**
5.7					fS		S	**Bar**
5.8					fS			
5.9					fS			
6					fS	**Bar**		
6.1								
6.2								
6.3								
6.4								
6.5								
6.6								
6.7								
6.8								
6.9								
7								
7.1								
7.2								
7.3								
7.4								
7.5								

	MOV-SLX-54		MOV-SLX-57 (OSL)					
Depth meters	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation
0.1	SiL		cS					
0.2	SiL		cS					
0.3	SiL		cS					
0.4	SiL		fS					
0.5	SiC		fS					
0.6	SiC		fS					
0.7	SiL		fS					
0.8	SiC		fS					
0.9	SiL		fS	**Bar Sands**				
1	SiL		fS					
1.1	SiL		fS					
1.2	SiL		fS					
1.3	L	**Overbank Fines**	fS					
1.4	SL		LS					
1.5	LS		LS					
1.6	LS		fS					
1.7	SL		fS					
1.8	L		fS					
1.9	L		LS	**Bar**				
2	SiL							
2.1	SL							
2.2	LS							
2.3	LS							
2.4	LS							
2.5	LS							

	MOV-SLX-54		MOV-SLX-57 (OSL)					
Depth meters	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation
2.6	LS	**Overbank Fines**						
2.7	LS							
2.8	LS							
2.9	LS							
3	LS	**Bar Sands**						
3.1	LS							
3.2	LS							
3.3	LS							
3.4	LS							
3.5	LS							
3.6	LS							
3.7	LS							
3.8	LS							
3.9	fS							
4	fS	**Bar**						
4.1								
4.2								
4.3								
4.4								
4.5								
4.6								
4.7								
4.8								
4.9								
5								

	MOV-SL-3 (OSL)		MOV-SL-7		MOV-SL-10		MOV-SL-11	
Depth meters	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation
0.1	SiL		SiL		SiC		SiL	
0.2	SiL		SiL		SiC		SiL	
0.3	SiL		L	**Overbank Fines**	SiC		SiL	
0.4	SiL		L		SiC		SiL	
0.5	SiL		L		SiC		SiL	**Overbank Fines**
0.6	SiL		SL		SiC		SiL	
0.7	SiL		fS		SiC		SiL	
0.8	SiC		fS		SiC		SiL	
0.9	SiC		fS		SiC		L	
1	SiC		fS	**Bar Sands**	SiC		L	
1.1	C		fS		C		fS	
1.2	C		fS		C		fS	
1.3	SiL	**Splay**	fS		C	**Channel Fill**	fS	**Bar Sands**
1.4	SiL		fS	**Bar**	C		fS	
1.5	SiL				C		fS	
1.6	L				C		fS	**Bar**
1.7	L				C			
1.8	L				C			
1.9	SiL				C			
2	SiL				C			
2.1	SiL				C			
2.2	SiL				C			
2.3	L				C			
2.4	L				C			
2.5	L				C			

	MOV-SL-3 (OSL)		MOV-SL-7		MOV-SL-10		MOV-SL-11	
Depth meters	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation
2.6	L				L			
2.7	L				LS			
2.8	L				LS			
2.9	L				LS			
3	SL				C			
3.1	SL				LS			
3.2	L				LS			
3.3	L				LS			
3.4	L				C			
3.5	L				C			
3.6	L				C			
3.7	L				L			
3.8	L	**Splay**			L	**Channel Fill**		
3.9	SiL				L			
4	SiL				L			
4.1	SL				SiL			
4.2	SL				SiL			
4.3	SL				SiL			
4.4	SL				L			
4.5	SL				L			
4.6	L				L			
4.7	SL				L			
4.8	L				L			
4.9	SL				L			
5	SL				L			

	MOV-SL-3 (OSL)		MOV-SL-7		MOV-SL-10		MOV-SL-11	
Depth meters	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation
5.1	SL				L			
5.2	SL				L			
5.3	SL	**Bar Top**			L	**Channel Fill**		
5.4	SL				L			
5.5	SL				LS			
5.6	SL	**Buried Bar**			LS			
5.7	SL				cS	**Channel Bottom**		
5.8					cS			
5.9					cS	**Channel**		
6								
6.1								
6.2								
6.3								
6.4								
6.5								
6.6								
6.7								
6.8								
6.9								
7								
7.1								
7.2								
7.3								
7.4								
7.5								

	MOV-SL-12		MOV-SL-18		MOV-SL-22		MOV-SL-27	
Depth meters	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation
0.1	SiL	**Overbank Fines**	LS	**Overbank Fines**	SiC	**Overbank Fines/Splay**	SiL	**Overbank Fines**
0.2	L		LS		SiC		L	
0.3	SiL		L		SiC		L	
0.4	SiL		L		SiC		L	
0.5	SiL		L		SiC		L	
0.6	SiL		L		SiC		L	
0.7	fS	**Bar Sands**	SL		SiC		L	
0.8	fS		LS		SiC		L	
0.9	fS		LS		SiC		L	
1	fS		LS	**Bar Sands**	SiC		L	
1.1	fS		cS		SiC		L	
1.2	fS		cS		SiL		L	
1.3	fS		cS		SiL		L	
1.4	fS		cS		SiL		SiL	
1.5	fS		cS		SiL		SiL	
1.6	fS	**Bar**	cS		SiL		SiL	
1.7			cS		SiL		L	
1.8			cS		SiL		L	
1.9			cS		SiL		L	
2			cS	**Bar**	SiL		L	
2.1					fS	**Bar Sands**	SiL	
2.2					fS		L	
2.3					fS		L	
2.4					fS		L	
2.5					fS		L	

	MOV-SL-12		MOV-SL-18		MOV-SL-22		MOV-SL-27	
Depth meters	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation
2.6					fS		L	
2.7					fS		SL	
2.8					fS	**Bar Sands**	SL	
2.9					fS		SL	
3					fS		SL	**Overbank Fines**
3.1					fS	**Bar**	SL	
3.2							SL	
3.3							SL	
3.4							SL	
3.5							SL	
3.6							SL	
3.7							SL	
3.8							SL	
3.9							SL	**Bar Sands**
4							SL	
4.1							SL	
4.2							fS	
4.3							fS	
4.4							fS	**Bar**
4.5								
4.6								
4.7								
4.8								
4.9								
5								

	MOV-SL-29		MOV-SL-40		MOV-SL-47 (OSL)		MOV-SL-49 (OSL)	
Depth meters	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation
0.1	SL		cS		C		C	
0.2	SL		cS		C		SiC	
0.3	SL		cS		C		SiC	
0.4	SL		cS		C		SiL	
0.5	SL		cS		C	**Overbank Fines**	L	
0.6	SL		cS	**Bar Sands**	SL		SL	
0.7	SL		cS		LS		SL	**Overbank Fines**
0.8	L		cS		LS		SL	
0.9	L		cS		LS		SL	
1	L		cS		fS		L	
1.1	L		cS		fS		LS	
1.2	L		cS	**Bar**	fS		LS	
1.3	L	**Channel Fill**			fS		SL	
1.4	L				fS		fS	
1.5	SiL				fS		fS	
1.6	SiL				fS		fS	
1.7	SiL				fS		fS	**Bar Sands**
1.8	SiL				fS	**Bar Sands**	fS	
1.9	SiL				fS		fS	
2	SiL				fS		fS	**Bar**
2.1	L				fS			
2.2	SiL				fS			
2.3	SiL				fS			
2.4	SiL				fS			
2.5	C				fS			

	MOV-SL-29		MOV-SL-40		MOV-SL-47 (OSL)		MOV-SL-49 (OSL)	
Depth meters	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation
2.6	C				fS			
2.7	C				fS			
2.8	C				fS			
2.9	C				fS			
3	C				fS			
3.1	C				fS			
3.2	C				fS	**Bar Sands**		
3.3	C				fS			
3.4	C				fS			
3.5	SiL				fS			
3.6	L				fS			
3.7	L				fS			
3.8	L	**Channel Fill**			fS			
3.9	L				fS			
4	L				fS	**Bar**		
4.1	C							
4.2	C							
4.3	C							
4.4	SiC							
4.5	SiL							
4.6	L							
4.7	L							
4.8	L							
4.9	L							
5	L							

	MOV-SL-29		MOV-SL-40		MOV-SL-47 (OSL)		MOV-SL-49 (OSL)	
Depth meters	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation
5.1	L							
5.2	L	**Channel Fill**						
5.3	L							
5.4	L	**Channel**						
5.5								
5.6								
5.7								
5.8								
5.9								
6								
6.1								
6.2								
6.3								
6.4								
6.5								
6.6								
6.7								
6.8								
6.9								
7								
7.1								
7.2								
7.3								
7.4								
7.5								

	MOV-SLX-50 (OSL)							
Depth meters	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation
0.1	LS							
0.2	LS							
0.3	LS							
0.4	LS							
0.5	LS							
0.6	LS							
0.7	LS							
0.8	LS							
0.9	LS							
1	LS	**Bar Sands**						
1.1	LS							
1.2	LS							
1.3	LS							
1.4	LS							
1.5	LS							
1.6	LS							
1.7	LS							
1.8	LS							
1.9	LS							
2	LS	**Bar**						
2.1								
2.2								
2.3								
2.4								
2.5								

	MOV-OSW-1		MOV-OSW-2		MOV-OSW-4		MOV-OSW-6	
Depth meters	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation
0.1	NA	**Missing Log Page**	SiL	**Overbank Fines**	C	**Splay/Channel Fill**	SiC	**Splay**
0.2	NA		SiL		C		SiCL	
0.3	NA		SiL		C		SiL	
0.4	NA		SiL		C		L	
0.5	NA		SiL		C		SL	
0.6	NA		SiC		C		SL	
0.7	NA		SiL		C		SL	
0.8	NA		SiL		C		SL	
0.9	NA		L		C		L	
1	NA		L		C		L	
1.1	NA		L		SiC		SiCL	
1.2	NA		L		SiC		SiC	
1.3	NA		L		SiC		SiCL	
1.4	NA		SL		SiCL		SiL	
1.5	NA		SL		SiCL		SiL	
1.6	NA		L		C		L	
1.7	NA		SL		C		L	
1.8	NA		SL		SiC		L	
1.9	NA		SL		SiC		L	
2	NA		LS		SiC		SiL	
2.1	C	**Channel Fill**	SL		SiC		SiL	
2.2	C		L		SiC		L	
2.3	C		LS	**Bar Sands**	SiC		SiL	
2.4	C		LS		SiC		SiL	
2.5	C		LS		SiC		SiL	

	MOV-OSW-1		MOV-OSW-2		MOV-OSW-4		MOV-OSW-6	
Depth meters	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation
2.6	C		LS		SiC		SiL	
2.7	C		LS		C	**Splay/Channel Fill**	SiL	
2.8	C		LS		SiCL		SiL	
2.9	C		LS		SiCL	**Splay/Channel**	SiL	
3	C		LS		SL		SiC	
3.1	C		LS				C	
3.2	C		LS	**Bar Sands**			C	
3.3	C	**Channel Fill**	LS				C	
3.4	C		fS				L	
3.5	C		fS				SL	**Splay**
3.6	C		fS				SL	
3.7	C		fS				SL	
3.8	C		fS				LS	
3.9	C		fS				LS	
4	C		fS	**Bar**			LS	
4.1	fS						LS	
4.2	fS						LS	
4.3	fS	**Channel Bottom**					LS	
4.4	fS						LS	
4.5	fS						LS	**Splay**
4.6	fS							
4.7	fS	**Channel**						
4.8								
4.9								
5								

	MOV-OSW-12 (OSL)		MOV-OSW-14		MOV-OSW-15		MOV-OSW-18	
Depth meters	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation
0.1	SiC		C		SiC		SiL	
0.2	SiL	**Overbank Fines**	C		SiC		SiL	
0.3	SiL		SiC		SiL		L	
0.4	L		SiC		SiL		SL	
0.5	LS		SiC		L		SL	
0.6	fS		SiC		L		LS	
0.7	fS		SiC		SiL		LS	
0.8	fS		SiC		SiL		LS	
0.9	fS	**Bar Sands**	C		L		LS	
1	fS		C		L	**Overbank Fines**	LS	
1.1	fS		SiC	**Overbank Fines**	SiL		LS	
1.2	fS		SiC		SL		LS	
1.3	fS		SiC		L		LS	
1.4	fS	**Bar**	SiC		L		LS	
1.5			SL		L		LS	
1.6			SiC		L		SiL	
1.7			SiC		L		SiL	
1.8			L		SL		SiL	
1.9			SL		LS		C	
2			SL		LS		C	
2.1			SL		LS		C	
2.2			SL		LS	**Bar Sands**	C	
2.3			LS		LS		C	
2.4			LS	**Bar Sands**	LS		C	
2.5			fS		LS		SiC	

	MOV-OSW-12 (OSL)		MOV-OSW-14		MOV-OSW-15		MOV-OSW-18	
Depth meters	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation
2.6			fS		LS		C	
2.7			L		LS		SiC	
2.8			SL		LS		SiL	
2.9			SL		fS		C	
3			SL		LS		SiC	
3.1			SL		LS		C	
3.2			fS		LS		C	
3.3			fS		LS		SiL	
3.4			fS		LS		C	
3.5			fS	**Bar Sands**	LS	**Bar Sands**	SL	**Overbank Fines**
3.6			fS		LS		SL	
3.7			fS		LS		SL	
3.8			fS		fS		SL	
3.9			fS		fS		SL	
4			fS		fS		SL	
4.1			fS		fS		C	
4.2			fS		fS		SiC	
4.3			fS		fS		SL	
4.4			fS	**Bar**	fS		C	
4.5					fS	**Bar**	SL	
4.6							LS	
4.7							LS	
4.8							LS	**Bar Sands**
4.9							LS	
5							LS	

	MOV-OSW-12 (OSL)		MOV-OSW-14		MOV-OSW-15		MOV-OSW-18	
Depth meters	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation
5.1							LS	
5.2							LS	
5.3							LS	
5.4							LS	
5.5							fS	
5.6							fS	
5.7							fS	
5.8							LS	**Bar Sands**
5.9							LS	
6							LS	
6.1							fS	
6.2							fS	
6.3							fS	
6.4							fS	
6.5							fS	
6.6							fS	**Bar**
6.7								
6.8								
6.9								
7								
7.1								
7.2								
7.3								
7.4								
7.5								

	MOV-OSW-19		MOV-OSW-21		MOV-OSW-22		MOV-OSW-27	
Depth meters	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation
0.1	SL	**Bar Sands**	C	**Splay**	C	**Splay**	C	
0.2	L		C		C		C	
0.3	SL		SiC		L		C	
0.4	LS		SiC		SL		C	
0.5	fS		SiC		SL		C	
0.6	fS		C		SiL		SiC	
0.7	fS		C		SL		L	
0.8	fS		C		LS		L	
0.9	fS		C		fS		SL	
1	fS		C		SL		SL	
1.1	fS	**Bar**	C		fS		SiC	
1.2			C		fS		SiC	
1.3			C		fS		SiC	
1.4			C		SiL		SiC	
1.5			C		SiL		SiC	
1.6			SiC		SL		SiC	
1.7			SiC		SiC		SiC	
1.8			L		SiC		C	
1.9			L		SiC		C	
2			L		C		C	
2.1			C		C		SiC	
2.2			C		SL		SiC	
2.3			C		SL		SiC	
2.4			C		SiL		SiC	
2.5			C		SiL		SL	

	MOV-OSW-19		MOV-OSW-21		MOV-OSW-22		MOV-OSW-27	
Depth meters	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation
2.6			C		C		SL	
2.7			SL		C		SL	
2.8			SiL		C		LS	
2.9			SL		SiL		LS	
3			SL		L	**Splay**	LS	
3.1			SiL		SL		LS	
3.2			fS		SL		fS	
3.3			fS	**Splay**	SL		LS	
3.4			fS		SL		C	**Splay**
3.5			SL		LS		C	
3.6			SiL		LS		SL	
3.7			SiL		LS		SL	
3.8			SiC		fS		SL	
3.9			SiC		fS		SL	
4			SiC		fS		SL	
4.1			SL		fS	**Bar Sands**	SL	
4.2			fS		fS		SL	
4.3			fS		fS		SL	
4.4			fS	**Bar Sands**	fS		LS	
4.5			fS		fS		LS	
4.6			fS		fS		LS	
4.7			fS	**Buried Bar**	fS		LS	**Bar Sands**
4.8					fS	**Splay/Bar**	fS	
4.9							fS	
5							fS	

	MOV-OSW-19		MOV-OSW-21		MOV-OSW-22		MOV-OSW-27	
Depth meters	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation
5.1							fS	
5.2							fS	
5.3							fS	
5.4							fS	
5.5							fS	
5.6							fS	
5.7							fS	
5.8							fS	**Bar Sands**
5.9							fS	
6							fS	
6.1							fS	
6.2							fS	
6.3							fS	
6.4							fS	
6.5							fS	
6.6							fS	**Bar**
6.7								
6.8								
6.9								
7								
7.1								
7.2								
7.3								
7.4								
7.5								

	MOV-OSW-29		MOV-OSW-31		MOV-OSW-32		MOV-OSW-35	
Depth meters	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation
0.1	C		SiC		L		LS	
0.2	C		SiC		LS		LS	
0.3	C		SiC		LS		LS	
0.4	C		SiC		LS		LS	
0.5	C		SiC		LS		LS	
0.6	C		SiC		fS		SL	
0.7	C		L		SL		LS	
0.8	C		SiC		SL		SL	
0.9	C		SiC		SL		SL	
1	SiC		SiC		SL		SL	
1.1	SiC		SiL	**Splay**	SiL		SL	
1.2	SiC		L		SiL		SiL	
1.3	SiC	**Channel Fill**	SL		SiL	**Splay**	SiL	**Splay**
1.4	C		LS		SiL		SiC	
1.5	C		LS		SiL		SiC	
1.6	C		SL		SiL		SiL	
1.7	C		SL		SiC		SiC	
1.8	C		SL		SiL		SiL	
1.9	C		SL		SiC		SL	
2	C		LS		L		SL	
2.1	C		SL		L		SL	
2.2	C		fS		C		SL	
2.3	C		fS	**Bar Sands**	SL		SL	
2.4	C		LS		SL		SiL	
2.5	C		LS		SL		SL	

	MOV-OSW-29		**MOV-OSW-31**		**MOV-OSW-32**		**MOV-OSW-35**	
Depth meters	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation
2.6	C	**Channel Fill**	fS	**Bar Sands**	L	**Splay**	SL	**Splay**
2.7	C		fS		SiC		SL	
2.8	C		fS		SiC		L	
2.9	C		fS		SiC		SiC	
3	C		fS		SiC		C	
3.1	C		fS		SiC		C	
3.2	C		fS		SL		C	
3.3	C		fS		C		LS	
3.4	C		fS		SiL		LS	
3.5	C		NA	**Lost Samples**	C		SiL	
3.6	C		NA		SiC		L	
3.7	C		NA		SL		SL	
3.8	C		fS	**Bar Sands**	SL		SL	
3.9	C		fS		SL		L	
4	C		fS		SL		SL	
4.1	C		fS		SL		L	
4.2	C		NA	**Samples Lost**	SL		SiL	
4.3	C		NA		LS		L	
4.4	C		NA		SL		SL	
4.5	C		NA		SL		SiC	
4.6	C		NA		SL		SiC	
4.7	C		NA		SL		SL	
4.8	C		NA		SL		SL	
4.9	C		NA		LS	**Bar Sands**	fS	**Bar Sands**
5	C		NA		LS		fS	

	MOV-OSW-29		MOV-OSW-31		MOV-OSW-32		MOV-OSW-35	
Depth meters	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation
5.1	SiC		NA		LS		fS	
5.2	SiL		NA		LS		fS	
5.3	C		NA		fS		fS	
5.4	C		NA		fS	**Bar Sands**	fS	
5.5	C		NA		fS		fS	
5.6	C		NA	**Samples Lost**	fS		fS	**Bar Sands**
5.7	C		NA		fS		fS	
5.8	C		NA		fS	**Splay**	fS	
5.9	C		NA				fS	
6	C		NA				fS	
6.1	C		SiC				fS	
6.2	C	**Channel Fill**	SiC				fS	**Splay/Bar**
6.3	C		SiC					
6.4	C		SiC					
6.5	C		SiC					
6.6	C		SiC					
6.7	C		SiC					
6.8	C		SiC	**Buried Channel Fill**				
6.9	C		SiC					
7	SiC		SiC					
7.1	C		SiC					
7.2	C		SiC					
7.3	C		SiC					
7.4	C	**Channel**	SiC					
7.5			SiC					

	MOV-OSW-29		MOV-OSW-31		MOV-OSW-32		MOV-OSW-35	
Depth meters	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation
7.6			SiC	**Channel Fill**				
7.7			SiC	**Splay/Bar**				
7.8								
7.9								
8								
8.1								
8.2								
8.3								
8.4								
8.5								
8.6								
8.7								
8.8								
8.9								
9								
9.1								
9.2								
9.3								
9.4								
9.5								
9.6								
9.7								
9.8								
9.9								
10								

	MOV-OSW-39		MOV-OSW-41		MOV-OSW-52		MOV-OSW-57	
Depth meters	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation
0.1	C	**Overbank Fines**	SiC	**Splay/Overbank Fines**	SiC	**Splay**	C	**Overbank Fines**
0.2	C		SiC		SiC		SiC	
0.3	C		SL		SiC		SiC	
0.4	C		SL		SiC		SiL	
0.5	C		SL		SiC		L	
0.6	C		SL		L		C	
0.7	C		SL		L		C	
0.8	C		SL		L		SiC	
0.9	C		C		SiL		SiC	
1	C		C		SiL		C	
1.1	C		C		SiL		C	
1.2	C		SiC		SiL		C	
1.3	C		C		SiC		C	
1.4	C		C		fS		SiC	
1.5	C		C		fS		SiC	
1.6	SiC		C		SL		fS	**Bar Sands**
1.7	C		C		SiC		fS	
1.8	C		C		SiC		fS	
1.9	SiC		SL		SiL		fS	
2	C		SL		L		fS	
2.1	LS	**Bar Sands**	SL		SiL		NA	**Samples Lost**
2.2	fS		SL		L		NA	
2.3	fS		fS	**Bar Sands**	L		NA	
2.4	fS		fS		L		NA	
2.5	fS		fS		SL		NA	

	MOV-OSW-39		MOV-OSW-41		MOV-OSW-52		MOV-OSW-57	
Depth meters	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation
2.6	fS		fS		SL		NA	
2.7	fS		fS		SL		NA	**Samples Lost**
2.8	fS		fS		SL		NA	
2.9	fS		fS		SL		NA	
3	fS	**Bar Sands**	fS		SL		fS	**Bar Sands**
3.1	fS		fS		SiC		fS	
3.2	fS		fS	**Bar Sands**	SiC		fS	**Bar**
3.3	fS		fS		C			
3.4	fS		fS		C			
3.5	fS		fS		C			
3.6	fS	**Bar**	fS		C			
3.7			fS		C			
3.8			fS		C	**Channel Fill**		
3.9			fS		C			
4			fS	**Splay/Bar**	C			
4.1					C			
4.2					C			
4.3					C			
4.4					C			
4.5					C			
4.6					C			
4.7					L			
4.8					C			
4.9					C			
5					C			

	MOV-OSW-39		MOV-OSW-41		MOV-OSW-52		MOV-OSW-57	
Depth meters	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation
5.1					L			
5.2					L			
5.3					C			
5.4					C	**Channel Fill**		
5.5					C			
5.6					C			
5.7					C			
5.8					C	**Channel**		
5.9								
6								
6.1								
6.2								
6.3								
6.4								
6.5								
6.6								
6.7								
6.8								
6.9								
7								
7.1								
7.2								
7.3								
7.4								
7.5								

	MOV-LS-17		MOV-LS-28		MOV-LS-29		MOV-LS-30 (OSL)	
Depth meters	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation
0.1	L	**Channel Fill**	SiL	**Overbank Fines**	SiC	**Overbank Fines**	C	**Overbank Fines**
0.2	fS		SiL		SiC		C	
0.3	SiC		SiL		L		SiC	
0.4	C		SL		L		SiC	
0.5	SiC		SL		LS	**Bar Sands**	C	
0.6	SiC		SL		fS		SiC	
0.7	SiC		LS		fS		SiL	
0.8	C		LS		fS		SiL	
0.9	C		LS		fS		SiC	
1	C		LS		fS		C	
1.1	C		LS		fS		C	
1.2	SiC		LS		fS		L	
1.3	C		LS		fS		L	
1.4	SiC		LS		fS		L	
1.5	SiC		SL		fS		L	
1.6	SiC		SiL		fS		L	
1.7	C		SiL		fS	**Bar**	L	
1.8	SiC		L				SiL	
1.9	SiC		L				SL	
2	C		SiC				fS	**Bar Sands**
2.1	C		SiC				fS	
2.2	C		SiC				fS	
2.3	C		fS				fS	
2.4	C		fS				fS	
2.5	C		L				fS	

	MOV-LS-17		MOV-LS-28		MOV-LS-29		MOV-LS-30 (OSL)	
Depth meters	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation
2.6	C		SiL				fS	
2.7	C		SiL				fS	
2.8	C		L				fS	**Bar Sands**
2.9	C		SiC				fS	
3	C		L				fS	
3.1	C		L				fS	**Bar**
3.2	C		SiL	**Overbank Fines**				
3.3	SiC		L					
3.4	SiC		L					
3.5	SiL		SL					
3.6	SiL		L					
3.7	SiL	**Channel Fill**	SiL					
3.8	SiL		L					
3.9	SiL		fS					
4	SiL		fS					
4.1	SiL		fS					
4.2	SiL		fS					
4.3	SiL		fS	**Bar Sands**				
4.4	SiL		fS					
4.5	SiL		fS					
4.6	SiL		fS					
4.7	SiL		fS					
4.8	NA	**Sample Lost**	fS	**Bar**				
4.9	LS	**Channel Bottom**						
5	LS							

	MOV-LS-17		MOV-LS-28		MOV-LS-29		MOV-LS-30 (OSL)	
Depth meters	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation
5.1	LS	**Channel Bottom**						
5.2	LS							
5.3	LS							
5.4	LS							
5.5	fS							
5.6	LS							
5.7	LS							
5.8	LS	**Channel**						
5.9								
6								
6.1								
6.2								
6.3								
6.4								
6.5								
6.6								
6.7								
6.8								
6.9								
7								
7.1								
7.2								
7.3								
7.4								
7.5								

	MOV-LS-31		MOV-LS-32		MOV-LS-34 (OSL)		MOV-LS-51	
Depth meters	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation
0.1	C		fS		SiC		fS	
0.2	SiC		fS		SiC		fS	
0.3	SiC		fS		SiC		fS	
0.4	SiC		fS		SiC		fS	
0.5	C		fS		SiC	**Overbank Fines**	fS	
0.6	SiC		fS		SiC		fS	
0.7	C		fS		C		fS	**Bar Sands**
0.8	C		fS	**Bar Sands**	SiC		fS	
0.9	C		fS		SiC		fS	
1	SiC		fS		SiL		fS	
1.1	C		fS		fS		fS	
1.2	SiC		fS		fS		fS	
1.3	SiC	**Channel Fill**	fS		fS		fS	
1.4	C		fS		fS		fS	
1.5	SiC		fS		fS	**Bar Sands**	fS	**Bar**
1.6	C		fS	**Bar**	fS			
1.7	SiC				fS			
1.8	C				fS			
1.9	SiC				fS			
2	C				fS			
2.1	C				SiL			
2.2	C				SiL			
2.3	C				L	**Mud Sheet**		
2.4	C				L			
2.5	C				SiC			

	MOV-LS-31		MOV-LS-32		MOV-LS-34 (OSL)		MOV-LS-51	
Depth meters	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation
2.6	C				C			
2.7	C				SiC			
2.8	C				C	**Mud Sheet**		
2.9	C				C			
3	C				C			
3.1	C				SL			
3.2	C				cS			
3.3	C	**Channel Fill**			cS			
3.4	C				cS			
3.5	C				fS			
3.6	C				fS			
3.7	C				fS			
3.8	C				fS	**Bar Sands**		
3.9	C				fS			
4	C				fS			
4.1	fS				fS			
4.2	fS	**Channel Bottom**			fS			
4.3	fS				fS			
4.4	fS				fS			
4.5	fS	**Channel**			fS			
4.6					fS			
4.7					fS	**Bar**		
4.8								
4.9								
5								

	MOV-BNC-9		MOV-BNC-31					
Depth meters	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation
0.1	SiCL	**Overbank Fines**	SiC	**Channel Fill**				
0.2	SiCL		SiC					
0.3	SiCL		SiC					
0.4	SiCL		SL					
0.5	SiC		C					
0.6	SiC		C					
0.7	SiC		SiC					
0.8	SiC		C					
0.9	SiC		C					
1	SiC		SiC					
1.1	SiC		SiC					
1.2	SiL		C					
1.3	SiL		C					
1.4	SiC		C					
1.5	SiC		C					
1.6	SiC		C					
1.7	NA		C					
1.8	SiCL		C					
1.9	SiC		C					
2	SiC		C					
2.1	LS	**Bar Sands**	C					
2.2	LS		C					
2.3	LS		C					
2.4	LS		C					
2.5	LS		SiC					

	MOV-BNC-9		MOV-BNC-31					
Depth meters	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation
2.6	LS		SiC					
2.7	fS		C					
2.8	fS		C					
2.9	fS		C					
3	mS	**Bar Sands**	C					
3.1	mS		C					
3.2	mS		C					
3.3	mS		C					
3.4	mS		C					
3.5	mS	**Bar**	C					
3.6			C					
3.7			C					
3.8			C	**Channel Fill**				
3.9			C					
4			C					
4.1			SiL					
4.2			SiC					
4.3			SiC					
4.4			SiC					
4.5			SiC					
4.6			SiC					
4.7			C					
4.8			C					
4.9			SiC					
5			SiC					

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<tr><th></th><th colspan="2">MOV-BNC-9</th><th colspan="2">MOV-BNC-31</th><th colspan="2"></th><th colspan="2"></th></tr>
<tr><th>Depth meters</th><th>Facies</th><th>Interpretation</th><th>Facies</th><th>Interpretation</th><th>Facies</th><th>Interpretation</th><th>Facies</th><th>Interpretation</th></tr>
<tr><td>5.1</td><td></td><td></td><td>C</td><td rowspan="6">Channel Fill</td><td></td><td></td><td></td><td></td></tr>
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	MOV-MD-4		MOV-MD-5		MOV-MD-11		MOV-MD-13	
Depth meters	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation
0.1	C		SiC		LS		C	
0.2	C		C		LS		SiC	
0.3	C		C		LS		C	
0.4	SiC		C		LS		SiC	
0.5	C		C		LS		SiC	
0.6	C		C		LS		C	
0.7	C		SiC		LS		C	
0.8	SiC		SiC		LS		C	
0.9	C		C		SL		C	
1	SiC		SiL		SiL		C	
1.1	SiC	**Natural Levy Deposits**	SiL		SiC		C	
1.2	SiC		SiL		L		C	
1.3	SiC		LS	**Natural Levy Deposits**	SiC	**Overbank Fines**	C	**Channel Fill**
1.4	C		SL		SiC		C	
1.5	SiC		L		SiC		L	
1.6	C		SiC		SiC		L	
1.7	L		SiC		SiC		L	
1.8	SL		C		SiC		L	
1.9	SL		C		SL		L	
2	SL		L		SL		L	
2.1	SL		C		SL		SL	
2.2	SL		C		SL		L	
2.3	fS		L		SL		L	
2.4	fS	**Bar Sands**	SL		L		SL	
2.5	fS		L		SL		L	

	MOV-MD-4		MOV-MD-5		MOV-MD-11		MOV-MD-13	
Depth meters	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation
2.6	LS		L	**Natural Levy Deposits**	LS	**Overbank Fines**	L	**Channel Fill**
2.7	fS		L		LS		L	
2.8	NA	**Samples Lost**	L		LS		L	
2.9	NA		L		L		mS	**Channel Bottom**
3	fS	**Bar topped by Levy**	SL		LS		NA	
3.1	fS		LS		LS		SL	
3.2	NA		SL		SL		mS	
3.3	NA		SL		L		NA	
3.4			fS	**Bar Sands**	SiC		fS	
3.5			fS		L		fS	**Channel**
3.6			LS		SL	**Bar Sands**		
3.7			LS		LS			
3.8			LS		fS			
3.9			SL		fS			
4			SL		fS			
4.1			LS		fS			
4.2			LS		fS			
4.3			fS		fS			
4.4			fS		fS			
4.5			fS		fS			
4.6			NA		LS			
4.7			fS		fS			
4.8			fS		LS			
4.9			fS	**Bar topped by Levy**	fS			
5			fS		SL			

	MOV-MD-4		MOV-MD-5		MOV-MD-11		MOV-MD-13	
Depth meters	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation
5.1					C	**Clay Drape**		
5.2					SL	**Bar**		
5.3								
5.4								
5.5								
5.6								
5.7								
5.8								
5.9								
6								
6.1								
6.2								
6.3								
6.4								
6.5								
6.6								
6.7								
6.8								
6.9								
7								
7.1								
7.2								
7.3								
7.4								
7.5								

	MOV-MD-37		MOV-MD-38		MOV-MD-39		MOV-MD-40	
Depth meters	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation
0.1	LS		SL		SiL		SiC	
0.2	LS		SiC		SiL		SiC	
0.3	LS		C		SiC		C	
0.4	LS		C	**Overbank Fines**	SL		C	
0.5	LS		C		C		SiC	
0.6	LS		SiC		C		C	
0.7	SL		SL		SiC		C	
0.8	SL		LS		SL		C	
0.9	SL		fS		SL		SiL	
1	SL		fS		LS		C	
1.1	fS		fS		LS		C	
1.2	fS		fS		LS		C	
1.3	fS	**Bar Sands**	fS		LS	**Active Channel Fill**	C	**Overbank Fines**
1.4	fS		LS		LS		C	
1.5	fS		SL		SL		C	
1.6	fS		LS		SL		SiL	
1.7	fS		LS	**Bar Sands**	SL		SL	
1.8	fS		fS		SL		SiL	
1.9	fS		LS		NA		L	
2	fS		LS		SiL		SiL	
2.1	fS		LS		C		L	
2.2	fS		SL		SiL		SiL	
2.3	fS		LS		SL		SL	
2.4	fS		fS		LS		SiL	
2.5	fS		SL		LS		SL	

	MOV-MD-37		MOV-MD-38		MOV-MD-39		MOV-MD-40	
Depth meters	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation
2.6	fS	**Bar Sands**	LS	**Bar Sands**	LS	**Channel Bottom**	SL	**Overbank Fines**
2.7	fS		LS		LS		L	
2.8	fS	**Bar**	LS		LS		C	
2.9			LS		LS		SL	
3			fS	**Bar**	LS		SL	
3.1					LS		LS	**Bar Sands**
3.2					fS		LS	
3.3					fS		SL	
3.4					LS		LS	
3.5					LS		SL	
3.6					LS		LS	
3.7					LS		SL	
3.8					LS		LS	
3.9					LS	**Channel**	LS	
4							fS	
4.1							fS	
4.2							fS	**Bar**
4.3								
4.4								
4.5								
4.6								
4.7								
4.8								
4.9								
5								

	MOV-MD-45		MOV-MD-47					
Depth meters	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation
0.1	LS		C					
0.2	LS		C					
0.3	SL		C					
0.4	SL		C					
0.5	SL		C					
0.6	SL		C	**Overbank Fines**				
0.7	L		SiC					
0.8	L		SiCL					
0.9	SL		SiL					
1	SL		SL					
1.1	SL		SL					
1.2	SL		SL					
1.3	L	**Splay**	LS					
1.4	L		fS					
1.5	SL		fS					
1.6	SiL		fS					
1.7	C		fS					
1.8	SiL		fS	**Bar Sands**				
1.9	SiL		fS					
2	SiC		fS					
2.1	SiC		fS					
2.2	SiC		fS					
2.3	SiC		fS					
2.4	C		fS					
2.5	C		fS	**Bar**				

	MOV-MD-45		MOV-MD-47					
Depth meters	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation
2.6	C	**Mud Flat**						
2.7	SiC							
2.8	C							
2.9	C							
3	C							
3.1	C							
3.2	SiC	**Splay**						
3.3								
3.4								
3.5								
3.6								
3.7								
3.8								
3.9								
4								
4.1								
4.2								
4.3								
4.4								
4.5								
4.6								
4.7								
4.8								
4.9								
5								

	MOV-HE-1		MOV-HE-5		MOV-HE-7		MOV-HE-8	
Depth meters	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation
0.1	NA	**Road Fill**	SiL	**Road Fill**	SiC	**Road Fill**	L	**Road Fill**
0.2	SiCL	**Back Swamp**	L		SiL		L	**Splay**
0.3	SiCL		L	**Back Swamp**	SiC	**Splay**	L	
0.4	SiL		SL		SiL		L	
0.5	SiL		L		SiL		L	
0.6	SiCL		L		SiL		SiL	
0.7	L		LS		L		L	
0.8	SiC		SL		L		L	
0.9	SiC		L		SiC		L	
1	SiC		L		L		L	
1.1	SiC		SiC		LS		LS	
1.2	SiC		SiC		S		SL	
1.3	SiC		SiC		LS		L	
1.4	SiC		SiC		SiL		SiC	**Back Swamp**
1.5	SiC		SiC		SiC	**Back Swamp**	SiC	
1.6	SiC		SiC		SiC		SiC	
1.7	SiC		SiC		SiC		SiC	
1.8	SiC		SiC		SiC		C	
1.9	SiC		SiC		SiC		C	
2	SiC		SiC		SiC		SiC	
2.1	C		SiC		C		SiC	
2.2	C		SiC		C		C	
2.3	SiC		SiC		C		C	
2.4	SiC		SiC		C		SiC	
2.5	SiC		SiC		C		C	

	MOV-HE-1		MOV-HE-5		MOV-HE-7		MOV-HE-8	
Depth meters	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation
2.6	SiC		SiC		C		C	
2.7	SiC		SiC		C		C	
2.8	SiC		C		C		SiC	
2.9	SiC		C		C		SiC	
3	SiC		SiC		C		C	
3.1	SiC		SiC		C		SiC	
3.2	SiC		SiC		C		C	
3.3	SiC		C		C		SiC	
3.4	SiC		SiC		C		C	
3.5	SiC		SiC		C		C	
3.6	SiC		C		C		C	
3.7	SiC		C		C		C	
3.8	SiC	**Back Swamp**	C	**Back Swamp**	C	**Back Swamp**	C	**Back Swamp**
3.9	C		C		C		C	
4	SiC		C		C		C	
4.1	SiC		SiC		C		C	
4.2	SiC		SiC		C		C	
4.3	SiC		C		C		C	
4.4	SiC		C		C		C	
4.5	SiC		SiC		C		C	
4.6	SiC		SiC		C		C	
4.7	SiC		SiC		C		C	
4.8	SiC		SiC		C		C	
4.9	SiC		SiC		C		C	
5	SiC		SiC		C		C	

	MOV-HE-1		MOV-HE-5		MOV-HE-7		MOV-HE-8	
Depth meters	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation
5.1	SiC		SiC		C		C	
5.2	SiC		SiC		C		C	
5.3	SiC		SiC		C		C	
5.4	SiC	**Back Swamp**	SiC		C		C	
5.5	SiC		SiC	**Back Swamp**	C		C	**Back Swamp**
5.6	SiC		SiC		C		C	
5.7	SiC		SiC		C		C	
5.8	SiC	**Back Swamp**	SiC		C	**Back Swamp**	C	
5.9			SiC		C		C	
6			SiC		C		C	**Back Swamp**
6.1			SiC	**Back Swamp**	C			
6.2					C			
6.3					C			
6.4					C			
6.5					C			
6.6					C	**Back Swamp**		
6.7								
6.8								
6.9								
7								
7.1								
7.2								
7.3								
7.4								
7.5								

	MOV-HE-19							
Depth meters	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation
0.1	SiL	**Overbank Fines**						
0.2	SiL							
0.3	SiL							
0.4	SiL							
0.5	SiL							
0.6	LS							
0.7	LS							
0.8	LS							
0.9	LS							
1	SL							
1.1	L							
1.2	S							
1.3	S							
1.4	L							
1.5	SiL							
1.6	SiC							
1.7	SiL							
1.8	SiC							
1.9	SiC	**Channel Fill**						
2	SiC							
2.1	SiC							
2.2	C							
2.3	C							
2.4	C							
2.5	C							

	MOV-HE-19							
Depth meters	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation
2.6	C	**Channel Fill**						
2.7	C							
2.8	C							
2.9	C							
3	C							
3.1	C							
3.2	C							
3.3	C							
3.4	C							
3.5	C							
3.6	C							
3.7	L							
3.8	S	**Channel Bottom**						
3.9	S							
4	S							
4.1	S							
4.2	S							
4.3	S							
4.4	S							
4.5	S							
4.6	S							
4.7	S							
4.8	S							
4.9	S							
5	S							

	MOV-HE-19							
Depth meters	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation	Facies	Interpretation
5.1	S	**Channel Bottom**						
5.2	S							
5.3	S	**Channel**						
5.4								
5.5								
5.6								
5.7								
5.8								
5.9								
6								
6.1								
6.2								
6.3								
6.4								
6.5								
6.6								
6.7								
6.8								
6.9								
7								
7.1								
7.2								
7.3								
7.4								
7.5								

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BIOGRAPHICAL INFORMATION

Daniel Earl Carlin is a Texas native who received his Bachelors of Science in Geosciences at The University of Texas at Dallas, May 2009. He loved geology as a child, but never knew it was a subject even taught until attending The University of Texas at Dallas. He met Dr. John Holbrook in the spring of 2008 while John was teaching undergraduate Sedimentology and Stratigraphy to UT Arlington, which was transmitted via live video conferencing to The University of Texas at Dallas. Daniel discovered his enjoyment of sedimentology and fluvial geomorphology over the course of the class. He sought out John Holbrook, who took him on as a master's student. Daniel loves geology, fluvial geomorphology and structural geology specifically. He hopes to return to academia in a few years and pursue his PhD.